GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA 13, GEORGIA

January 12, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 1
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of December, 1961.

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

In addition to the senior personnel who participated in research under the previous contract, the following three persons devote part of their time to the project: John A. Copeland, Charles Frahm, and Chang-Kiang Kuo. Copeland and Frahm are graduate students in Physics and Kuo is a graduate student in Electrical Engineering.

B. Detailed Studies

Work during the month was concerned mainly with preliminary design studies in preparation for the experiments proposed. The monochromator and vibrating reed electrometer for the photoemission experiment were ordered and some parts for the sample chamber have been made.

In order to study the tunnel emission phenomena Mr. C. K. Kuo has made a multiunit Al-Al_2O_3-Al diode and has observed an exponential I vs E curve, characteristic of a tunnel current, with a maximum current of about 10^{-8} amperes. At the moment this work is hampered by the lack of a suitable masking scheme for the Meissner high vacuum system.

Georgia Institute of Technology

BIOGRAPHICAL SKETCH

COPELAND, John A.--Graduate Research Assistant

Education

B.S. with Honor in Physics, Georgia Institute of Technology	August 1961
Graduate Student in Physics, Georgia Institute of Technology	September 1961-

Employment History

Radio station WAKE, Engineer	Summer 1958
Georgia Institute of Technology	
Student Assistant	1959-1961
Graduate Research Assistant	1961-Present

Experience Summary: Maintained electronic equipment and recorded commericals for radio station. Performed experimental studies on the effect of electric fields on the permeability of thin magnetic films. Had a principal part in the building of a low-temperature cryostat and electronics for studying phonon-electron interactions in tunnel diodes. Supervision of group now conducting studies of various solid-state properties of materials which might be used to develop solid-state electronic circuit elements. Developed sensitive hysteresis loop tracer for studying thin films in high vacuum.

Current Fields of Interest

Electrical and magnetic properties of solids; low temperature physics; thin films; solid-state electronics; ultra-high vacuum technique.

Honor Societies

Sigma Pi Sigma--Physics Honor Society	1961
Pi Mu Epsilon--Mathematics Honor Society	1961
Phi Kappa Phi--Scholastic Honor Society	1960
Tau Beta Pi--Engineering Honor Society	1960
Phi Eta Sigma--Scholastic Honor Society	1959

Georgia Institute of Technology

BIOGRAPHICAL SKETCH

FRAHM, Charles P.--Graduate Research Assistant

Education

A.A., Mason City Junior College (Iowa)	June 1958
B.S. in Physics, Georgia Institute of Technology	June 1961
Graduate Student in Physics, Georgia Institute of Technology	1961 - Present

Employment History

International Minerals and Chemical Corporation (East Point, Ga.), Analytical Chemist	1958 - 1959
Low and Company (Atlanta, Ga.), Analytical Chemist	1959 - 1960
Georgia Institute of Technology	
Teaching Assistant	1960 - 1961
Graduate Research Assistant	1961 - Present

Experience Summary: Performed routine fertilizer analyses and some special projects at International Minerals and Chemicals Corporation. Chemical analyses of water, oils, soaps, textiles, etc. at Low and Company. Taught one year of freshman mathematics as teaching assistant at Georgia Tech. Made infrared reflectance measurements on thin metal films as Graduate Research Assistant at Georgia Tech.

Current Fields of Interest

Theoretical studies in solid state physics, nuclear physics, and quantum physics.

Honor Societies

Tau Beta Pi--Engineering Honor Society	1961
Sigma Pi Sigma--Physics Honor Society	1961
Pi Mu Epsilon--Mathematics Honor Society	1962

Georgia Institute of Technology

BIOGRAPHICAL SKETCH

KUO, Chang-Kiang--Graduate Research Assistant

Education

B.S. in Electrical Engineering, Cheng Kung University	January 1958
Graduate Student in Electrical Engineering, Georgia Institute of Technology	1960 - Present

Employment History

Kong-I Broadcasting Station, Chia-I Taiwan	Summer 1957
Radar APG/30 Plant, Fire Control Department(Tainan Air Base)	1958 - 1960
Sen-Ao Steam Power Station, Keelung, Taiwan	Mar. 1960 - Jul. 1960
Georgia Institute of Technology Graduate Assistant	Sept. 1960 - Present

Experience Summary: Repairing and maintenance of radio transmitter and APG/30 radar. Operation of steam power plant in Taiwan. Made electronic equipment in Electrical Engineering Department. Constructed a high sensitivity hysteresis loop tracer at the Engineering Experiment Station. Operation of vacuum systems and making thin films at EES.

Current Fields of Interest

Hot electrons, tunneling effect.

Honor Societies

Eta Kappa Nu--Electrical Engineering Honor Society	1961

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

February 15, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of January, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

No changes in personnel were made during the month.

B. Detailed Studies

The quartz monochromator and the vibrating reed electrometer for the photoemission experiment have been received and the other parts that were to be constructed have been completed. Much of the effort was devoted to assembly of the sample chamber and connection to a suitable vacuum system. The light source (AH-6) electrical and cooling systems have not been finished yet.

Techniques for making thin film tunneling devices of aluminum-aluminum oxide have been improved. Temporarily, masks of aluminum foil are being used to decrease the size of the active areas. Most of the studies have been made on $Al-Al_2O_3-Al$ diodes but some $Al-Al_2O_3-Au$ diodes have also been examined. D. C. measurements have enabled us to identify two regions in the V-I characteristic; a low field region where I is proportional to E^2 and a higher field region in which I vs E follows the tunneling relation,

$$I = k_1 E^2 e^{-k_2/E}$$

Berry Pyron and L. W. Ross have been searching and studying the solid state literature in order to uncover pertinent references. No appreciable bibliography has been accumulated so far. Dr. Su's completed his paper.

C. Estimated Man Hours

	Hours
E. J. Scheibner	138
B. C. Pyron	184
K. L. Su	50
L. W. Ross	11
J. A. Copeland	108
C. K. Kuo	82
C. P. Frahm	69

D. Trips and Visits

Mr. John Blasingame visited us on January 2-3 to discuss the program. It was suggested that we should maintain cognizance of the work by Electro-Optical Systems.

Dr. E. J. Scheibner and John Copeland visited Texas Instruments in Dallas, Texas and Electro-Optical Systems in Pasadena, California, January 31-February 2, 1962.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS/cjh

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA 13, GEORGIA

March 7, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 3
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of February, 1962.

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

No changes in personnel were made during the month.

B. Detailed Studies

Assembly of the apparatus for the photoemission experiment is still in progress. Mr. Frahm, a graduate student in physics, who has been working on this phase has been unable to put in more than about ten hours a week. We intend to reassign certain tasks so that the work can proceed more uniformly.

Mr. Nave and Mr. Kuo have continued to make progress on the fabrication and measurement of $Al\text{-}Al_2O_3\text{-}Al$ tunnel emission diodes. Measurements have been made on a number of units in the forward and reverse directions and on one diode as a function of temperature. Analysis of the data from three separate diodes gives the same value of barrier height (0.66 ev). One would expect to obtain the same barrier height in either direction for the symmetrical $Al\text{-}Al_2O_3\text{-}Al$ structure. The failure to do so is perhaps an indication of the different interface properties and suggests that ultra-high vacuum techniques might well be needed for the preparation of the metal films. Electron micrographs of platinum-carbon replicas of the surface of aluminum oxide and tantalum oxide films were made.

After careful study of the general type of characteristics exhibited by the tunnel devices, Dr. Su has concluded that it would not be fruitful for him to limit himself to those devices. Rather he is now looking into the mathematical problems associated with distributed RC networks. Besides being of interest from the synthesis standpoint, these networks are attractive since they can be fabricated from multiple thin films.

C. Estimated Man Hours

	Hours.
E. J. Scheibner	109
B. O. Pyron	160
K. L. Su	34
L. W. Ross	No charge
J. A. Copeland	80
C. K. Kuo	80
C. P. Frahm	74

D. Trips and Visits

Dr. Scheibner and Mr. W. P. Edmondson visited ASD on February 27, 1962, to discuss work on the project.

Dr. Scheibner and Berry Pyron attended the symposium on hot electrons held at Philco Scientific Laboratory in Blue Bell, Pennsylvania, on February 28, 1962.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS/cjh

When the constants are evaluated the following results

$$J = 1.54 \times 10^{-6}(E^2/\Phi)\ \exp[-6.82 \times 10^{7}\ \frac{\Phi^{3/2}}{E}]\ .$$

The corresponding expression for thermionic emission with Schottky effect is:

$$J = (A^{'}T^{2}e^{\frac{-e\Phi_0}{kT}})\, e^{\frac{+e\Delta\Phi}{kT}}$$

The quantities involved in this equation are:

$$A^{'} = A(1-\gamma) = \frac{4\pi mk^{2}e}{h^{3}}\ (1-\gamma) = 120.4 \times 10^{4}\ (1-\gamma)\ \frac{\text{amp}}{m^{2}\ {}^{o}K}$$

γ = reflection coefficient

Φ = work function

$\Delta\Phi$ = lowering of surface barrier due to Schottky effect (a function of E).

With the constants evaluated numerically the equation becomes

$$J = 1.20 \times 10^{6}(1-\gamma)T^{2}\ \exp[-1.16 \times 10^{4}\ \frac{\Phi}{T}]\ \exp[0.4389\ \frac{\sqrt{E}}{T}]\ .$$

One can distinguish between the two phenomena by first plotting ln I/V^2 versus $1/V$ for the diodes and examine the slope of the curve. For the tunneling effect this slope is a constant of the form $K_2\Phi^{3/2}$.

By plotting ln I versus $V^{1/2}$ for constant temperature one should find that the slope is a constant for thermionic emission with Schottky effect. Moreover, plotting ln I/T^2 versus $1/T$ for a fixed voltage should give a constant slope while tunnel emission is supposedly temperature independent.

Experimental results (see curve I for Al-Al_2O_3-Al attached) show that for the higher voltages (>4 volts) the plot of ln I/V^2 versus $1/V$ is a good approximation to a straight line. The slope is also approximately constant with temperature. From the slope we have calculated the barrier height between Al and Al_2O_3 and find the same value (1.06 ev) for three separate diodes prepared on two different glass slides.

Curve II for a tantalum diode is a plot of ln I versus $\sqrt{V}$. For the region below V = 3 volts a good straight line slope is found indicative of thermionic emission with Schottky effect. It has not been determined as yet whether the slope in the low-voltage region depends on temperature as it should.

Our conclusions agree, in general, with those of others (see Phys Rev Letters 8, p. 267) that more than one mechanism is responsible for the V-I characteristics of thin film diodes.

2. Photoemission Experiment

The light source consisting of the AH-6 lamp, the housing and power supply has been completed and Mr. Frahm is measuring the photon flux at the exit slip of the monochromator as a function of wavelength. One needs to compromise on the slit width in order to obtain usable intensities with high resolution. Following the calibration he will proceed to preliminary experiments on the emission of electrons from Au into MgO in air at room temperature.

3. Synthesis Work

Dr. Su has continued to look at the problem of distributed RC networks with the hope of obtaining differential equations which can be readily solved, by approximation methods if necessary. Part of his effort is concerned with shaping the layers of the thin film transmission line to obtain desired terminal functions.

C. Estimated Man Hours

	Hours
E. J. Scheibner	176
B. O. Pyron	176
K. L. Su	40
L. W. Ross	No charge
J. A. Copeland	104
C. K. Kuo	62
C. P. Frahm	100.5
C. R. Nave	47

D. Trips and Visits

Dr. Scheibner and John Copeland attended the Solid State meeting of the American Physical Society in Baltimore, Maryland, March 26-29, 1962.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh

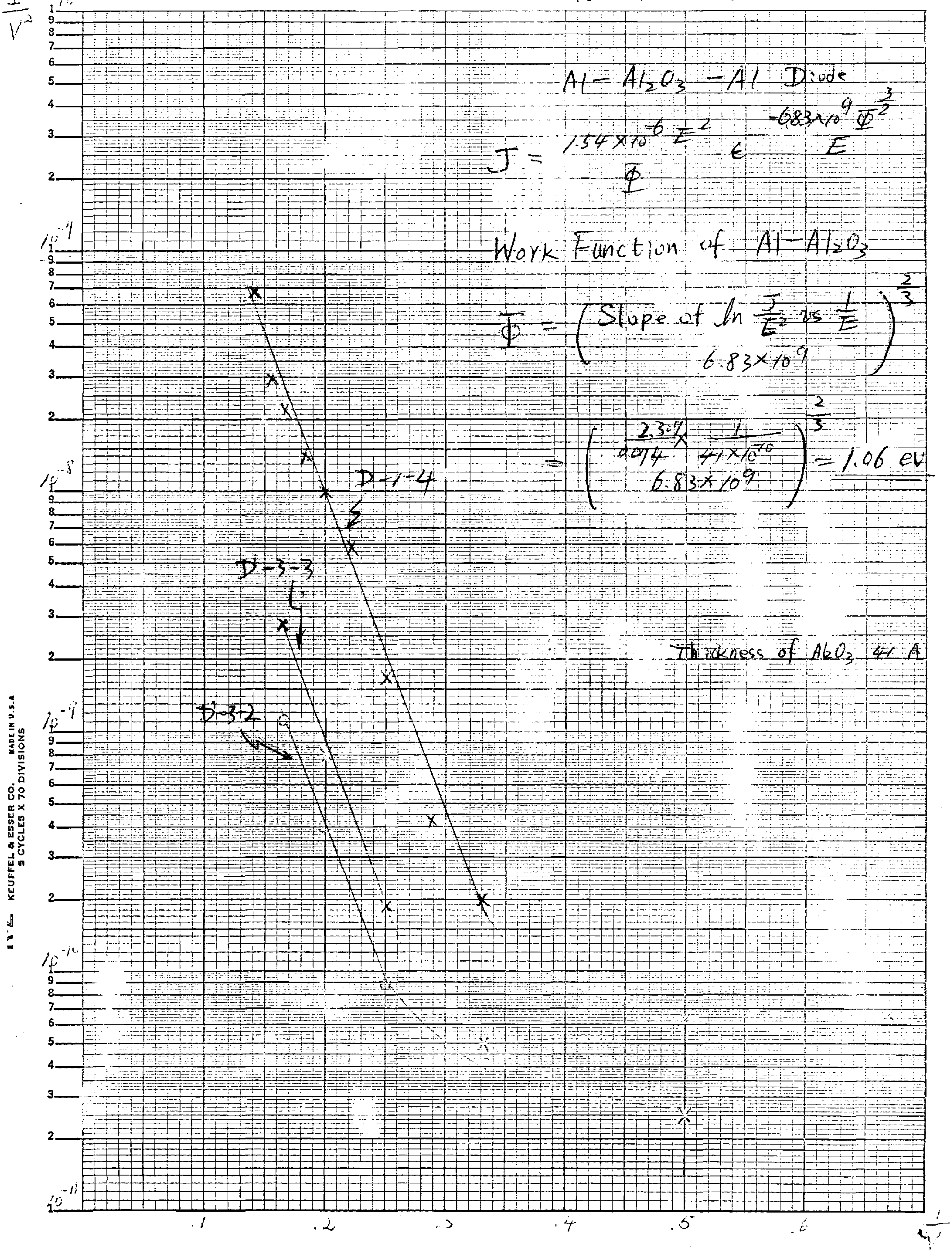
MATERIAL	ANODIZING ELECTROLYTES	ANODIZING VOLTAGES	THICKNESS OF OXIDE FILMS	TYPE OF METAL FILM	TEMPERATURE FOR MEASUREMENTS	MAX. CURRENT BEFORE BREAKDOWN	CHARACTERISTICS OF DIODES
Aluminum $Al-Al_2O_3-Al$	1. 3% tartaric acid adjusted to pH of 5.5 with NH_4OH	1.5 v. 3.1 v.	~14.0 Å/volt	evaporated	77°K (liquid nitrogen) 300°K (room) 373°K (boiling water)	2.4×10^{-6} amp. B.D. 5-7 volts.	- Generally unstable, rather low current densities - Initial emf of about 1v. across diode - less stable [illegible] liquid Nitrogen Tem[illegible] than room
Tantalum Ta_2O_5-Al	1. Same as above 2. 0.5% Na_2SO_4 *3 Ammonium Citrate $(NH_4)_2HC_6H_5O_7$	3.1 v.	10-11 Å/volt	sputtered	77°K 300°K 373°K	2.3×10^{-3} B.D. 1-10 volts.	- Currents generally stable, up to 10^3 larger than Al diode for same voltage - high [illegible] - more [illegible] N_2 temp. than at [illegible]
* Zirconium	1. Na_2SO_4 2. Boric acid adj. to pH of 8.0 with ammonia 3. KOH		27-30 Å/volt	evaporated			
* Titanium	1. Boric acid adjusted to pH of 8.0 with Ammonia.			evaporated			
* Niobium	1. Na_2SO_4			evaporated			

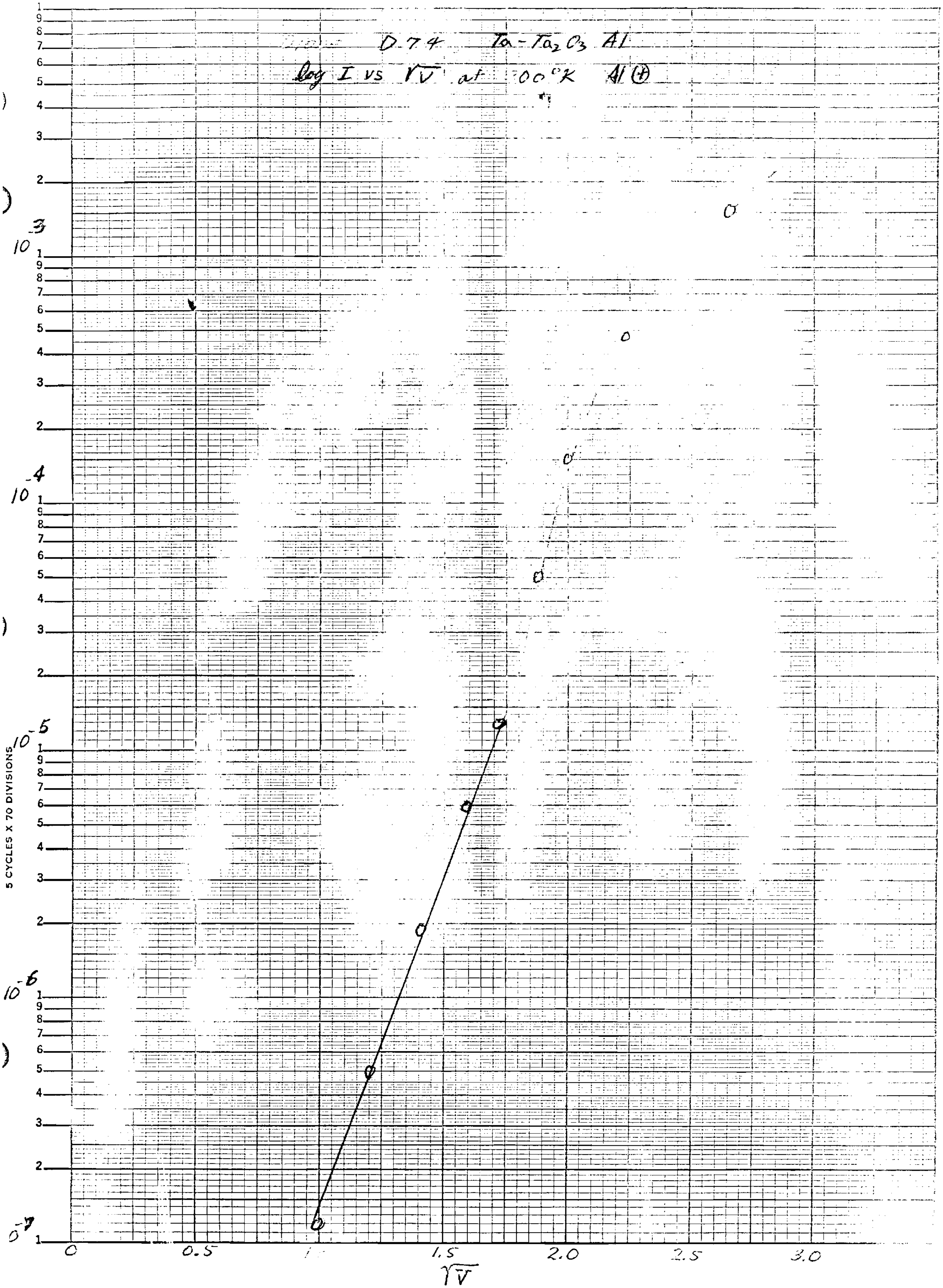
* proposed.

NOTE: 1. All oxide layers are barrier type anodic oxide films. Thickness of film [illegible] function of anodizing voltage only.

[illegible]

Work Function




D.74 Ta - Ta_2O_3 Al
log I vs $\sqrt{V}$ at 00°K Al (+)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1.5
2.0
2.5
3.0
$\sqrt{V}$
5 CYCLES X 70 DIVISIONS

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

May 14, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 5
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of April, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

No changes in personnel were made during the month.

B. Detailed Studies

1. Thin Film Diodes

The studies on the phenomena in thin films has been continued. During the past month measurements have been made of the current as a function of temperature between 77°K and 400°K on a Ti-TiO_2-Al structure (see attached graph). Voltage across the diode was kept constant at 2 volts. A logarithmic relation over the range from 150°K to 300°K is apparent while a negative current creep during measurements at the higher temperatures probably accounts for the lower current values in that range. Since the ratio of the active area to the geometric area is of the order of 10^{-3} it is suggested that an increase of area with temperature might be taking place. We expect to determine how the active area does change with temperature.

We have also studied the capacitance change with applied field for a Ta-Ta_2O_3-Al diode and find an increase with voltage possibly due to space charge effects.

2. Photoemission Experiment

Mr. Frahm has remeasured the photon flux at the exit slit of the monochromator using the thermopile and a sensitive galvanometer. There is an unexpected delay in these measurements because we are relocating our facilities.

3. Synthesis Work

Dr. Su is now looking into the possibility of constructing a band-stop filter using distributed resistances and capacitances. By putting a band-stop filter in the return path of a feedback amplifier, a band-pass characteristic can be obtained. The proposed scheme for realizing the band-stop filter is to modify the parameter values of the notch filter using uniform RC transmission lines. There appear to be some non-uniform RC lines that will supply the desired band-stop characteristic. The mathematical solution in closed form of characteristics of these non-uniform lines appears to be possible.

C. Estimated Man Hours

	Hours
E. J. Scheibner	126
B. O. Pyron	168
K. L. Su	50
J. A. Copeland	104
C. K. Kuo	100
C. P. Frahm	73
C. R. Nave	86

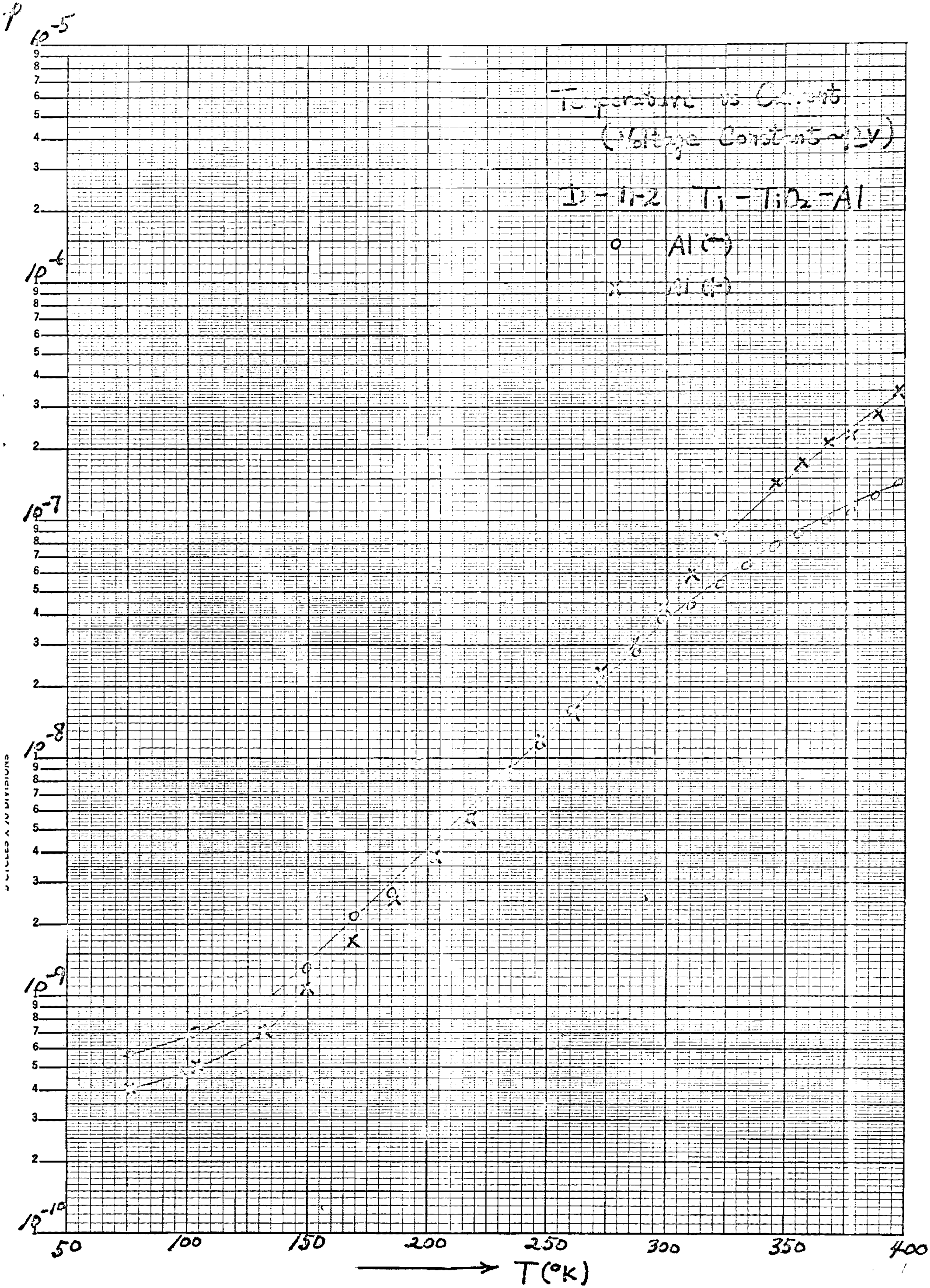
D. Trips and Visits

Dr. Scheibner and Mr. Edmondson visited ASD on April 5, 1962. Among other things discussed was the possibility of extending Dr. Su's work under Mr. Brenner's contract. A letter indicating Dr. Su's interest has been forwarded.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh



Temperature vs Current
(Voltage Constant = 2V)
D - 11-2 Ti - TiO2 - Al
o Al (+)
x Al (-)
I
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
50
100
150
200
250
300
350
400
T (°K)

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

June 7, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 6
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of May, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

No changes in personnel were made during the month.

B. Detailed Studies

1. Thin Film Diodes

The measurement of the current as a function of temperature has been continued. In a Ta-Ta_2O_3-Al diode, with Al side negative (4v), the current decreases with increasing temperature and the temperature dependence changes sign at around 0°C. The changing of barrier height between Al-Al_2O_3 and thermal instability probably accounts for the phenomenon.

It has been tried to improve Al-Al_2O_3-Al diodes by anodizing Al with different kinds of electrolytes. The current density is several hundred times larger by anodizing Al in Sodium Sulfate than in Tartaric Acid, but the characteristic is less stable.

2. Photoemission Experiment

No significant progress has been made on the photoemission experiment. Mr. Frahm has been devoting considerable time to his course work but expects to devote a greater portion to the project during the summer.

3. Synthesis Work

Mathematical expressions for the characteristics of a band-stop filter using distributed resistances and capacitances have been obtained and a computer program is being written to evaluate these expressions. After desirable characteristics are obtained from the computer data it is planned to fabricate thin film devices in order to verify the theory.

C. Estimated Man Hours

	Hours
E. J. Scheibner	69
B. O. Pyron	184
K. L. Su	30
J. A. Copeland	80
C. K. Kuo	80
C. P. Frahm	20
C. R. Nave	54.5

D. Trips and Visits

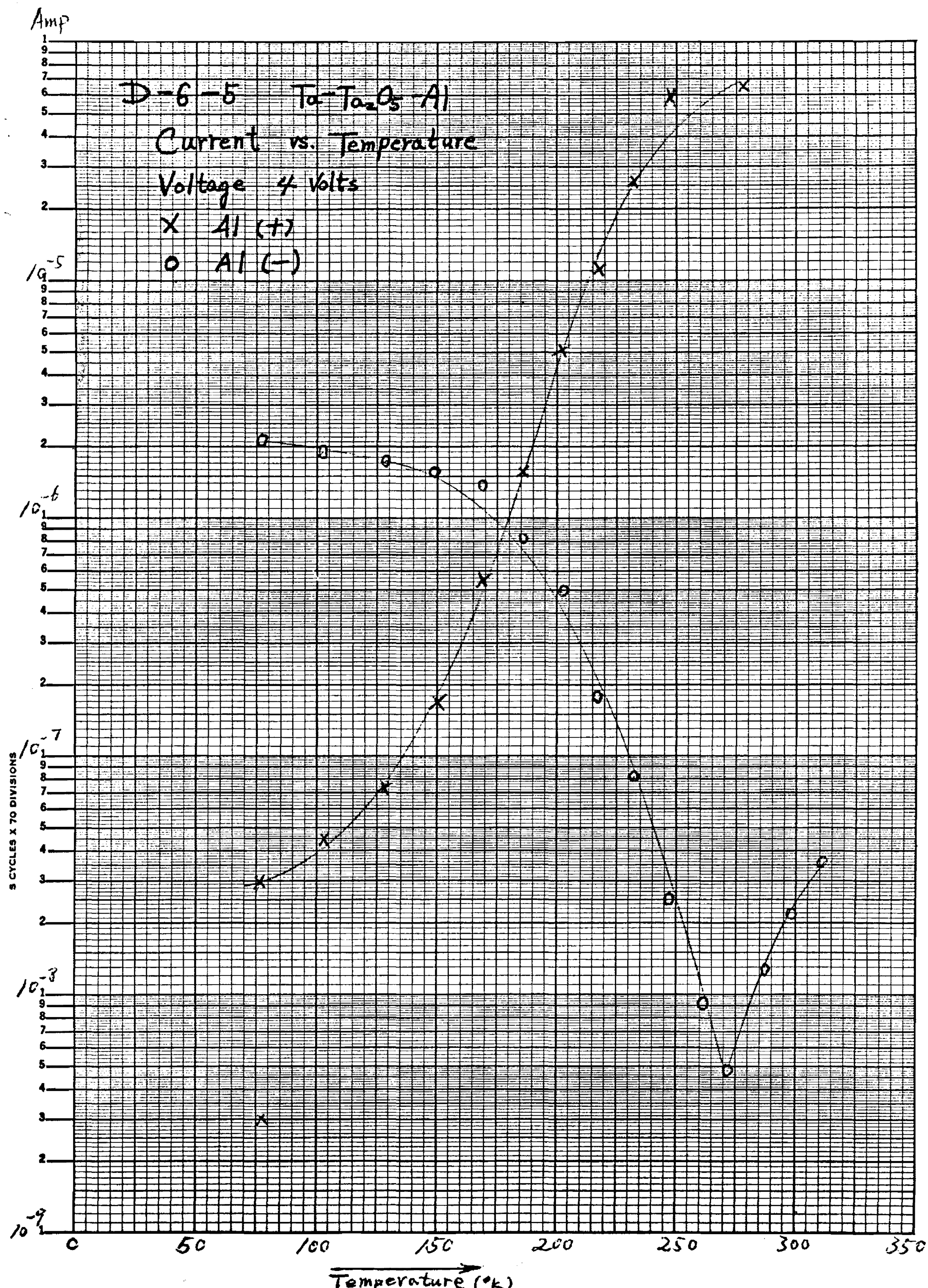
No trips or visits were made under the contract during the last month.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh

Enclosure



D-6-5 Ta-Ta2O5-Al
Current vs. Temperature
Voltage 4 Volts
X Al (+)
O Al (−)
Amp
10^-5
10^-6
10^-7
10^-8
10^-9
0
50
100
150
200
250
300
350
Temperature (°K)
5 CYCLES X 70 DIVISIONS

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

July 13, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 7
Contract No. AF33(657)-7867
Georgia Tech Project No. A-592
Month of June, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

On July 1, 1962, Dr. Scheibner became Chief of the Physical Sciences Division replacing Dr. A. L. Bennett who is devoting more time to research. Dr. Scheibner will continue to direct this project and remain in charge of the Solid State Group; however, he will be aided by Mr. B. R. Livesay who is assistant group leader.

B. Detailed Studies

1. Thin Film Diodes

Diodes have been made by anodizing titanium, tantalum, and aluminum films. Studies of the current transfer mechanisms in these diodes have been made and most of the diodes exhibit Schottky emission at low voltages (less than 1 volt) and tunneling at higher voltages. The possibility of space charge limited current at higher voltages with thicker films has been investigated.

Mr. C. K. Kuo has made several Al-Al_2O_3-Al diodes by oxidizing aluminum films in air at elevated temperatures. These diodes have exhibited the usual tunneling characteristics but are unstable and break down easily.

2. Photoemission Experiment

Mr. Frahm is continuing the preliminary measurements for the photoemission experiment. He is being assisted by Mr. James Maddox, an undergraduate who is being supported by the National Science Foundation. We have acquired a photomultiplier microphotometer for intensity measurements. A sample chamber and mirror housing have been built which allows the light from the monochromator to fall alternately on the sample and the photomultiplier. Mr. Maddox is calibrating the photomultiplier with the thermopile. The leakage current in the sample chamber has been reduced to 10^{-15} amperes.

Samples of Au on LiF and MgO have been prepared for the first measurements.

3. Synthesis Work

Mr. Livesay has prepared an ALGOL program of Dr. Su's band-stop filter problem. After a few revisions the program is now being run on the Burroughs 220 Data-Processing System. The characteristics of the filter have not been obtained yet.

4. Vacuum Techniques

Mr. Edmondson has received a Veeco motorized bell jar lift assembly and is in the process of installing it on the Meissner high vacuum system. It is hoped that this addition to the system will provide additional working space as well as improving the convenience of operation of the system. He is also examining the different electron beam evaporators available for use either with the Meissner system or separately.

C. Estimated Man Hours

	Hours
E. J. Scheibner	68
B. R. Livesay	20
B. O. Pyron	120
K. L. Su	30
J. A. Copeland	20
C. K. Kuo	60
C. P. Frahm	80
C. R. Nave	36

D. Trips and Visits

Mr. Edmondson visited Oak Ridge National Laboratories to examine their electron beam evaporator.

No other trips or visits were made under the contract during the last month.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh

Enclosure

BIOGRAPHICAL SKETCH

LIVESAY, BILLY R.--Assistant Research Physicist

Education

B.A. in Physics, Texas Christian University	1955
M.A. in Physics, University of Texas	1957

Employment History

University of Texas, Physics Department	
Teaching Assistant, School Years	1955-1956 1956-1957
Convair Ft. Worth Nuclear Lab	
Junior Engineer	Summer 1955
Nuclear Engineer	Summer 1956
U. S. Army, Ft. Monmouth, New Jersey, Second Lt.	1957-1958
Georgia Institute of Technology	
Instructor in Physics	1958-1961
EES, Research Associate	1960-1961
EES, Assistant Research Physicist	1961-Present

Experience Summary: Taught lab in Modern Physics at U. of Texas. Maintenance of nuclear instrumentation and set up experiments. Also established Secondary Standards Lab and worked out design of neutron spectrometer at Convair. Worked with group building MASER at Signal Corps Engineering Labs. Taught various sophomore physics courses at Georgia Tech. Worked with magnetic properties the past year.

Current Fields of Interest

Magnetic properties of solids; thin films.

Honor and Professional Societies

Sigma Pi Sigma--Honorary	1957
American Physical Society--Professional	1957-Present

Major Reports

1. "Total Neutron Cross Sections of Magnesium 2.35 - 2.85 Mev," Thesis (1957).
2. Section II of "Surface Properties of Magnetic Materials, Progress Report No. 1," on Contract AT-(40-1)-2755, February 1961, by E. J. Scheibner.

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

August 22, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 8
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of July, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

Mr. John Copeland is employed at Jet Propulsion Laboratory of Cal. Tech for the summer. He will return in the fall to continue his graduate studies. No other changes in personnel were made during the month.

B. Detailed Studies

1. Thin Film Diodes

Mr. Nave and Mr. Kuo have continued to examine the properties of thin film diodes whose dielectric layer is obtained by oxidizing in air or oxygen. Part of the effort during the month went toward changing over to a new evaporation system. With this system it is planned to fabricate the thin film diodes by a controlled sequence of operations.

2. Photoemission Experiment

Mr. Frahm and Mr. Maddox have continued to develop the instrumentation for this experiment. For some regions of the spectrum the microphotometer is over-sensitive so that we are now using a simple phototube. With the receipt of new components it has been possible to put some effort back into the construction of the vacuum system for measurements at different temperatures.

3. Vacuum Techniques

We have experienced two burnouts of the heating element of the diffusion pump in the Meissner system. Both instances appear to be attributable to the insertion of the heating element in such a fashion that there is poor thermal contact between the element and the boiler. Users of this type pump should be cautioned to maintain the proper orientation of the heating element when reassembling the pump.

Mr. Edmondson is still investigating various types of electron beam evaporation systems.

4. Synthesis Work

Dr. Su is continuing to study the application of thin film R-C distributed lines on filter circuits. The filter circuit used is shown in Fig. 1. The circuit employs one R-C monolithic transmission line and one external resistance. The line is a shaped sandwich of resistive, dielectric, and metallic layers as shown in Fig. 2. All layers are thin films of uniform thickness. This makes the product of resistance and capacitance per unit length a constant along the length of the line. The width of the line varies as the square of some trigonometric function.

Derivation of terminal functions of the filter network of Fig. 1 has been completed. It is found that some filters have an extremely wide stop band. A computer program has been completed for using Burroughs 220 Computer to calculate more filter characteristics when several parameters are being varied. Some typical characteristics are shown in Fig. 3.

Several approximate lumped-circuit models have been built to verify some of the analytical findings. One measured curve is given in Fig. 3. This curve does not coincide with either of the computed curves because they have different circuit parameters. They are shown together to illustrate the similarity between them in their general behavior.

A more thorough study of these filter characteristics is in progress. Preparation is also underway for fabricating several thin film models of the shaped R-C line in the laboratory.

C. Estimated Man Hours

	Hours
E. J. Scheibner	42
B. R. Livesay	42
B. O. Pyron	84
K. L. Su	33

C. Estimated Man Hours (Continued)

	Hours
C. K. Kuo	72
C. P. Frahm	152
C. R. Nave	92
W. P. Edmondson	84

D. Trips and Visits

Mr. John M. Blasingame, Jr. and Major Metscher visited us on July 20 to discuss the progress of work on the contract.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh

Enclosure

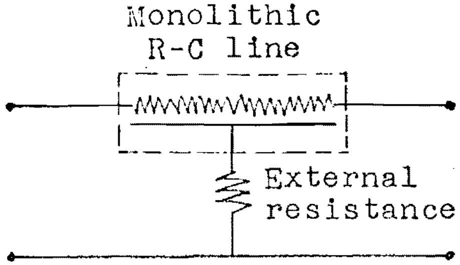


Fig. 1--Filter using monolithic line.

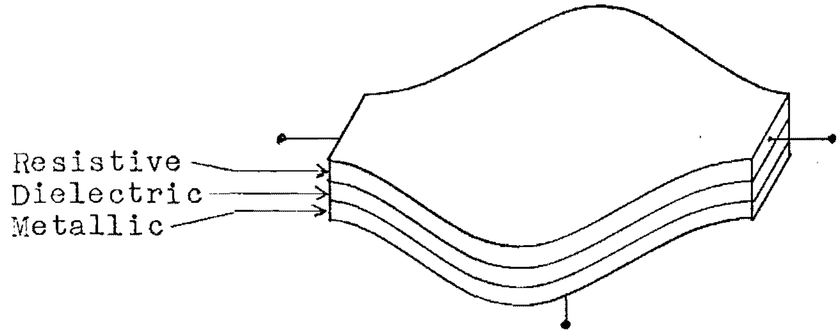


Fig. 2--Shaped monolithic R-C transmission line.

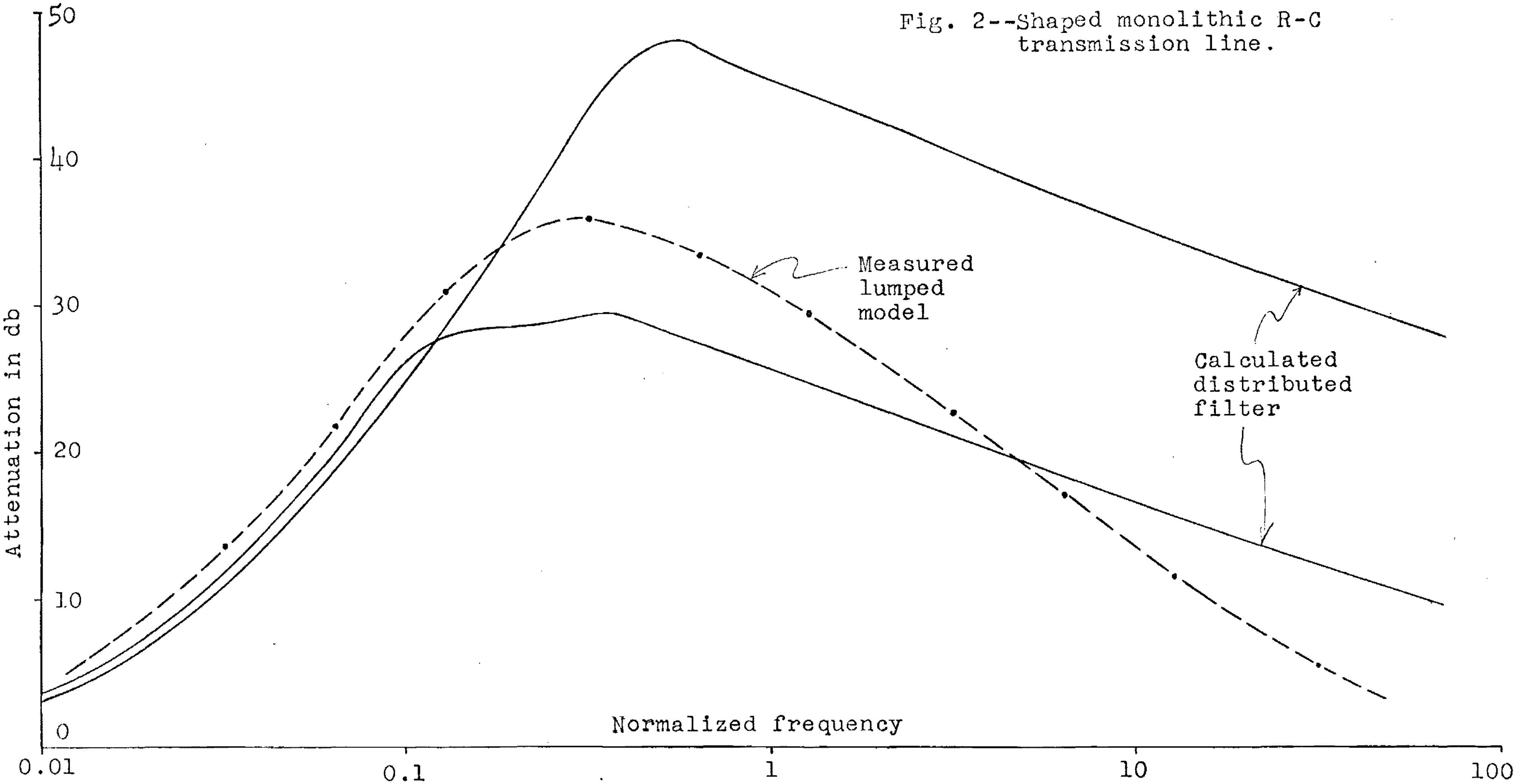


Fig. 3--Filter response characteristics

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

October 24, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 9
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Months of August and September, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

Mr. Stan Goldberg returned from a year's study at Technische Hochschule in Hannover, Germany where he studied the properties of thin antimony films by resistivity and infrared techniques.

Mr. Frahm has been awarded a National Defense Fellowship and will thus be able to reduce the amount of his direct charges to the contract. He will be assisted by two promising physics seniors, Mr. M. Wynn and Mr. K. Lane.

Mr. John Copeland has returned from his summer's employment at Jet Propulsion Laboratory but will devote all his time to magnetic studies not related to the project.

B. Detailed Studies

Mr. Pyron and Mr. Nave have been working on the various theories which might predict the V-I characteristics of the thin film diodes and have completed a careful analysis of the data. Further extensions of the theory as well as selected experiments are indicated by this work and we will propose to continue these studies with emphasis on the understanding of the phenomena.

Georgia Institute of Technology

BIOGRAPHICAL SKETCH

LANE, KENNETH DOUGLAS--Student Assistant

Education
Georgia Institute of Technology, Physics Major — Sept.1959-Present

Employment History
Georgia Institute of Technology
Physics Department, Laboratory Assistant — Mar.1962-June1962
Engineering Experiment Station, Student Assistant — Aug.1962-Present

Experience Summary: Supervised a Physics laboratory in the Physics Department. At present working on an experiment to determine the potential barrier that exists at the interface of a metal and a dielectric under various conditions of temperature and pressure.

Current Fields of Interest
Theoretical Physics, in particular, Relativity Theory

Georgia Institute of Technology

BIOGRAPHICAL SKETCH

WYNN, WILLIAM MICHAEL--Student Assistant

Education

Associate in Science in Electronics and Communications Technology, Southern Technical Institute	1957-1959
Georgia Institute of Technology, Physics Major	1959-Present

Employment History

Kraft Foods Co., Decatur, Ga.	Summers of 1957, 1958, 1959, 1960, and 1961
Sears, Roebuck and Company	Sept.1957-Dec.1957
Georgia Institute of Technology Engineering Experiment Station, Student Assistant	Feb.1962-Present

Experience Summary: Participated in measurements of the magnetic properties of thin films. Studied magnetic susceptibilities of ferromagnetic salts in alcohol-water solution as a function of concentration and field strength. Constructed a Quincke-type glass system for making these measurements and is now in the process of preparing a descriptive report on the method and associated problems with token emphasis on data evaluation.

Current Field of Interest

Quantum Mechanics

Societies

Tau Beta Pi	1961-Present
Sigma Pi Sigma	1962-Present
Phi Eta Sigma	1960-Present
Tau Alpha Pi (Southern Tech)	1958-Present

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA 13, GEORGIA

November 20, 1962

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 10
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of October, 1962

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, to determine their physical properties, their network properties, and their relationship to general solid state theory.

A. Personnel

No changes in personnel were made during the month.

B. Detailed Studies

Further effort was devoted to the analysis of the data from the thin film diode experiments in order to present as complete a picture as possible on the current status of our work and to determine the direction of future work. It is expected that emphasis will be placed on barrier phenomena with the photoemission study being the primary experimental approach.

The indication that it would be impossible to support Dr. Su's work under the continuation of the current contract makes it necessary that we consider alternative means for support. However, problems of immediate interest in the areas of thin film circuits and network synthesis are logical extensions of the present work.

1. Mathematical analysis of new RC distributed networks. An extension of the analysis completed from trigonometric lines to lines having other functional dependence of R and C. This analysis would provide a clue as to the general trend of the relationship between the shape of the line and its behavior.

2. Numerical analysis of composite RC lines. The cascading of various distributed elements to obtain optimum characteristics of the composite line.

3. Study of the effect of lossy dielectric material. When distributed networks are fabricated in thin film form the dielectric is not always the perfect material assumed. The effect of a shunt leakage conductance would be examined. It is not impossible that the effect may be beneficial rather than detrimental to the performance of the line.

A more detailed discussion of these and other problems in network synthesis will be forwarded.

C. Estimated Man Hours

	Hours
E. J. Scheibner	33
B. R. Livesay	37
B. O. Pyron	85
K. L. Su	40
C. K. Kuo	160
C. P. Frahm	None
C. R. Nave	None
W. P. Edmondson	37
W. M. Wynn	57
K. D. Lane	61
S. S. Goldberg	61

D. Trips and Visits

Mr. William Edmondson and Mr. Stan Goldberg attended the Ninth Annual Symposium of the American Vacuum Society in Los Angeles, California, October 31-November 2, 1962.

Respectfully submitted,

Edwin J. Scheibner
Project Director

EJS:cjh

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

16 July 1963

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 11
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of June, 1963

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, particularly the photoemission of electrons into dielectrics, and to develop electron beam techniques for evaporation of metals and dielectrics.

A. Personnel

Dr. James R. Stevenson became project director and as of June 10, 1963 is spending about one-third (1/3) of his time in direct supervision of the photoemission problem. In addition, Mr. Samuel Ng, Mr. Patrick Nettles, and Mr. Charles Wagner have been added to the group as student assistants. Mr. Kenneth Lane and Mr. Mike Wynn have remained with the group. Mr. Charles Frahm has resigned from this activity to spend more time on a thesis problem in theoretical physics.

B. Detailed Studies

The basic problem is a study of photoexcitation and transport in the region of a metal dielectric interface. As scattering and local fields may be considerably different from one thin dielectric film to another, a need for single crystal measurements is required to supplement thin film measurements. The experimental approach is to compare the photoexcitation and transport from metals into thin films of Al_2O_3, MgO and Ta_2O_5 and to take single crystal data on Al_2O_3 and MgO.

Mr. Lane and Mr. Ng are using the experimental arrangement which has been previously described. The sample chamber has been modified. Mr. Kuo has supplied some diode structures of Al-Al_2O_3-Al and voltage

REVIEW
PATENT 7-24 19 63 BY [signature]
FORMAT 10-9 19 63 BY [initials]

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

13 August 1963

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 12
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of July, 1963

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, particularly the photoemission of electrons into dielectrics, and to develop electron beam techniques for evaporation of metals and dielectrics.

A. Personnel

Mr. Goldberg has been assisting in the preparation of thin film samples. No other changes in personnel have taken place during the past month.

B. Detailed Studies

Mr. Lane and Mr. Ng are continuing their studies on Al-Al_2O_3-Al thin film diodes and on single crystals of MgO containing Al as an impurity. During the first part of the month a delay was encountered when the vibrating reed preamplifier was sent to California for repair and the experimental facility was moved to a different location. Voltage current characteristics have been made on a thin film sample to determine an operating voltage for measuring the effect of illumination. No reproducible results were obtained under illumination. Measurements on a single crystal of MgO with Al impurity showed a region of apparent negative resistance but this fact will have to be checked using a different type of electrode before any significance can be attached to the measurements. A noticeable effect of illumination has been measured. The photoemission aspects of the investigation will be stressed during the next month.

Mr. Nettles and Mr. Wynn have been investigating the effect of illumination on some MgO thin film diodes. Indications are that the upper evaporated electrode was opaque. The work on the MgO diodes has been dropped and work on Al_2O_3 diodes has been initiated until some degree of reproducibility can be obtained between the work of Mr. Ng and Mr. Lane and that of Mr. Nettles and Mr. Wynn. Mr. Nettles and Mr. Wynn will then concentrate on photoemission of the Ta_2O_5 diodes.

C. Estimated Man Hours

	Hours
J. R. Stevenson	58
E. J. Scheibner	No charge
B. O. Pyron	No charge
C. K. Kuo	56
C. R. Nave	No charge
W. P. Edmondson	88
W. M. Wynn	158
K. D. Lane	85
P. H. Nettles	107
S. S. T. Ng	168
C. E. Wagner	104
S. S. Goldberg	82

D. Trips and Visits

No trips or visits were made under contract during the past month.

Respectfully submitted,

James R. Stevenson
Project Director

JRS:cjh

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA 13, GEORGIA

OFFICE OF
ADMINISTRATOR OF RESEARCH

30 August 1963

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 13
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of August, 1963

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, particularly the photoemission of electrons into dielectrics, and to develop electron beam techniques for evaporation of metals and dielectrics.

A. Personnel

No changes in personnel have taken place in the past month.

B. Detailed Studies

Mr. Lane and Mr. Ng are making a modification in the evacuated sample chamber which they are using. The modification will result in more flexibility in mounting the samples and in the use of better vacuum conditions. The modification is about complete and measurements will be initiated on some tantalum-tantalum oxide samples to be supplied by Wright-Patterson. Some measurements have been made on films in air with no reproducible results on photoemission obtained. The presence of background currents in the sample suggest that the films are exhibiting a polarization effect and that photovoltaic measurements may be an alternative approach to the problem. However, a definite decision will not be made until films of tantalum oxide have been investigated in the new sample chamber.

Mr. Nettles and Mr. Wynn have made measurements under rough vacuum conditions and are now changing their system to go to a better vacuum. Mr. Wynn is making a Tolansky set-up to measure film thickness.

Mr. Wagner is making a sample chamber to attach to the vacuum monochromator and initial measurements in this region of the spectrum should be started this month.

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA 13, GEORGIA

11 October 1963

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 14
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of September, 1963

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, particularly the photoemission of electrons into dielectrics, and to develop electron beam techniques for evaporation of metals and dielectrics.

A. Personnel

Mr. Kenneth Kiang and Mr. Arthur Woodrum have joined the project as student assistants. Mr. S. Goldberg has resigned to continue his studies in Germany.

B. Detailed Studies

Mr. Lane has completed the new sample chamber and is now testing the chamber for vacuum and electrical leakage. Mr. Ng has been working on thin film preparations of Al_2O_3 dielectric between aluminum electrodes.

Mr. Wagner and Mr. Wynn have completed the sample chamber for use in the vacuum ultraviolet. Mr. Wagner is working on a cold-trap design for the instrument. Mr. Wynn has studied photoconductivity in a single crystal of MgO as a function of vacuum conditions and the results indicate that the use of a cold-trap is mandatory for reproducible results.

A-592

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

21 November 1963

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio

Attention: ASRNEA-2
Mr. John M. Blasingame, Jr.

Subject: Status Letter No. 15
Contract No. AF 33(657)-7867
Georgia Tech Project No. A-592
Month of October, 1963

REVIEW 12-6 1963 BY
PATENT FORMAT 12-11 1963 BY

Dear Sir:

The current contract is an extension of work carried out under Contract AF 33(616)-6028. The objectives of this work are to investigate certain phenomena which occur in composite layers of thin films, particularly the photoemission of electrons into dielectrics, and to develop electron beam techniques for evaporation of metals and dielectrics.

A. Personnel

No changes have been made in personnel.

B. Detailed Studies

The electron beam equipment has arrived and Mr. Edmondson is working on getting the equipment in operation. As Mr. Edmondson is planning on changing positions in the near future, we hope to have the equipment at an operating point before he leaves.

Mr. Lane and Mr. Ng have not made any measurements in vacuum because of a delay in shipping of a vacuum valve for the new sample chamber and a breakage taking place in the old one. Both of these should be back in operation in the near future.

Mr. Ng and Mr. Woodrum have been collaborating on making films and measuring thickness by the Tolansky technique.

Some delay has been encountered in the making of the cold trap for the vacuum ultraviolet work because of a change in purchasing procedure but we hope to have these measurements being made in the near future. Mr. Wagner and Mr. Wynn are collaborating on these measurements.

C. Estimated Man Hours

	Hours
J. R. Stevenson	No charge
E. J. Scheibner	No charge
B. O. Pyron	No charge
C. K. Kuo	47
W. P. Edmondson	92
W. M. Wynn	45
K. D. Lane	14
P. H. Nettles	No charge
S. S. T. Ng	102
C. E. Wagner	No charge
K. Kiang	9
A. Woodrum	18

D. Trips and Visits

No trips or visits were made under this contract during the past month.

Respectfully submitted,

for J. R. Stevenson
Project Director

JRS:md

AL-ASD-TDR-64-103

PHOTOELECTRIC PHENOMENA IN TUNNEL DIODE STRUCTURES

TECHNICAL DOCUMENTARY REPORT NO. AL-ASD-TDR-64-103

12 October 1964

Electronic Technology Division
AF Avionics Laboratory
Research and Technology Division
Wright-Patterson Air Force Base, Ohio

Project No. A-592

(Prepared under Contract No. AF 33(657)-7867 by Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia; J. R. Stevenson and E. J. Scheibner, Authors)

AL-ASD-TDR-64-103

PHOTOELECTRIC PHENOMENA IN TUNNEL DIODE STRUCTURES

TECHNICAL DOCUMENTARY REPORT NO. AL-ASD-TDR-64-103

12 October 1964

Electronic Technology Division
AF Avionics Laboratory
Research and Technology Division
Wright-Patterson Air Force Base, Ohio

Project No. A-592

Prepared under
Contract No. AF 33(657)-7867

Authors: J. R. Stevenson and E. J. Scheibner

FOREWORD

This report was prepared by the Engineering Experiment Station of the Georgia Institute of Technology under Contract No. AF 33 (657)-7867. The contract was initiated under Project No. A-592, "Phenomena, Theory, and Taxonomy." The work was administered under the direction of the Electronic Technology Laboratory, Aeronautical Systems Division. Mr. John M. Blasingame, Jr. was project engineer.

This report covers work conducted from 1 November 1962 to 30 January 1964.

ABSTRACT

The purpose of this investigation is to examine the possibility of obtaining data concerning the potential barrier at a metal-dielectric interface by the measurement of the photo-response of the interface. A phenomenological description of the barrier is described and a simple theory is developed as a tool for the analysis. The experimental approach to the problem is given and preliminary photoelectric data is presented and discussed. The current vs voltage characteristics of the thin film dielectrics are used as a control on sample characteristics.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

ROBERT D. LARSON, Chief
Electronic Research Branch
Electronic Technology Div.

Table of Contents

List of Figures

List of Figures (Continued)

I. Introduction to a Theoretical Model and Basis for Analysis

The purpose of this analysis is to investigate the potential energy function for an electron in the vicinity of a metal-dielectric interface by the analysis of experimental measurements on photo-electric emission at the interface. Photoelectric emission has proved to be a phenomenon of critical importance in the historical development of our understanding of quantum theory. Indeed, Hughes and Dubridge[1] described the Einstein photoelectric equation as "... perhaps the most important single equation in the whole quantum theory ... the key to a vast number of results outside the restricted domain of photoelectricity as well as within it." In the more limited sense, the study of photoelectric emission has provided important information concerning the properties of metal surfaces. The inconsistent values of work function obtained by the early workers in the field showed the need for working with clean surfaces of high purity and under extremely good vacuum conditions. The work of Apker[2] et al. initiated a new series of measurements on photoelectric emission from metals and non-metals which has been continued by a number of laboratories until the present.

On a theoretical basis, the Einstein equation provided a satisfactory starting point for the quantum theory but did not lend itself to a detailed analysis of photoelectric emission from metal surfaces. Fowler[3] gave a more complete treatment of photoelectric emission from metals into a vacuum and allowed for the variation of photoelectric yield with temperature. The theoretical treatment of Fowler is still adequate in the analysis of photoelectric emission from metals into vacuum when only the photoelectric work

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Manuscript released by authors 12 October 1964 for publication as an ASD Technical Documentary Report.

function is required. More recent measurements of photoelectric emission from metals, semiconductors, and insulators have necessitated a theoretical analysis of the distribution in energy of the emitted photoelectrons. Apker[4] et al. have treated this problem. With recent advances in the experimental and theoretical knowledge of the Fermi surfaces of metals, a more complete theoretical analysis of photoelectric emission from single crystal surfaces of metals into vacuum should be possible in the near future.

The present investigation is concerned with replacing the vacuum at the metal surface with a dielectric material. An analysis of emission from the metal into the dielectric should yield information concerning the potential energy function at the metal-dielectric interface similar to the photoelectric work function at a metal-vacuum interface. Several complicating features are present in the metal-dielectric interface which are not present in the metal-vacuum experiment. First, the formation of the interface can result in a diffusion of metal atoms into the dielectric and the atoms of the dielectric into the metal. This diffusion could result in a transition region of complex chemical structure. Regardless of the chemical structure, this particular investigation is concerned with a reproducible determination of the potential energy distribution in this transition region. Second, the electrons which are released by the incident light at the interface can become trapped in the dielectric and cause a space charge to develop. The actual current observed in the circuit will be reduced by the fraction of the total distance the charges move and the space charge will result in a time dependence of the observed current upon radiation. Third, the bulk photoconductivity in the dielectric must be examined to determine the contribution of the interface.

Before these complicating features are evaluated in terms of the present experiment, some information can be gained from an elementary point of view. In Figure 1, a dielectric with a work function of $e\phi_D$ is brought together with a metal of work function $e\phi_M$ such that $e\phi_D = e\phi_M$. If the electron affinity, χ, of the dielectric is defined as the energy from the bottom of the conduction band to the vacuum then the work function for electrons to get from the Fermi level of the metal into the conduction band of the dielectric is simply $e\phi_M - \chi$. Thus, the potential barrier for electrons to escape from the metal into the dielectric is less by an amount χ than the energy to escape from the metal into the vacuum.

Figure 2 shows the energy level scheme for the same dielectric as in Figure 1 coming in contact with a different metal such that $e\phi_M < e\phi_D$. If the Fermi levels are aligned in the equilibrium picture, then a space charge must exist at the interface, and a transition region exists. At large distances from the interface, the conditions are the same for the isolated materials. Thus at large distances the conduction band of the dielectric is an energy $e\phi_D - \chi$ above the Fermi level. However, at the interface the conduction band of the dielectric is an energy $e\phi_M - \chi$ above the Fermi level. Since the electrons from the metal must go a finite distance in the dielectric before contributing to the current in the circuit, the potential barrier for the detection of a current will be $e\phi$ such that $e\phi_M - \chi < e\phi < e\phi_D - \chi$. If the transition region is narrow then $e\phi$ will be approximately $e\phi_D - \chi$.

Figure 3 shows the third alternative in which the dielectric is the same but $e\phi_M > e\phi_D$. In equilibrium the Fermi levels are aligned and at large distances from the interface. The energy levels relative to the vacuum must be the same as for the isolated materials. At the interface the space charge gives a

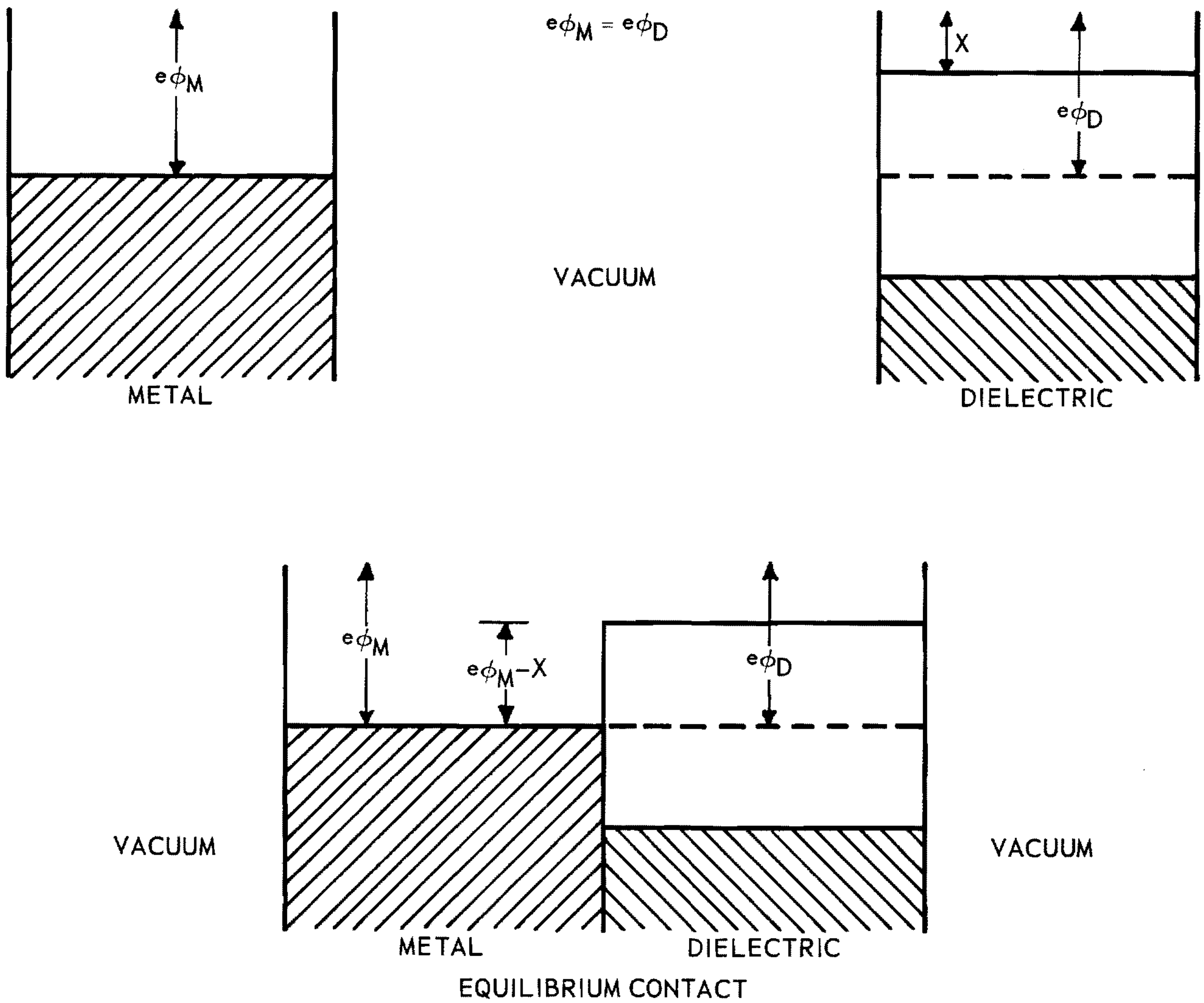

Figure 1. Metal-Dielectric Contact for $e\phi_M = e\phi_D$.

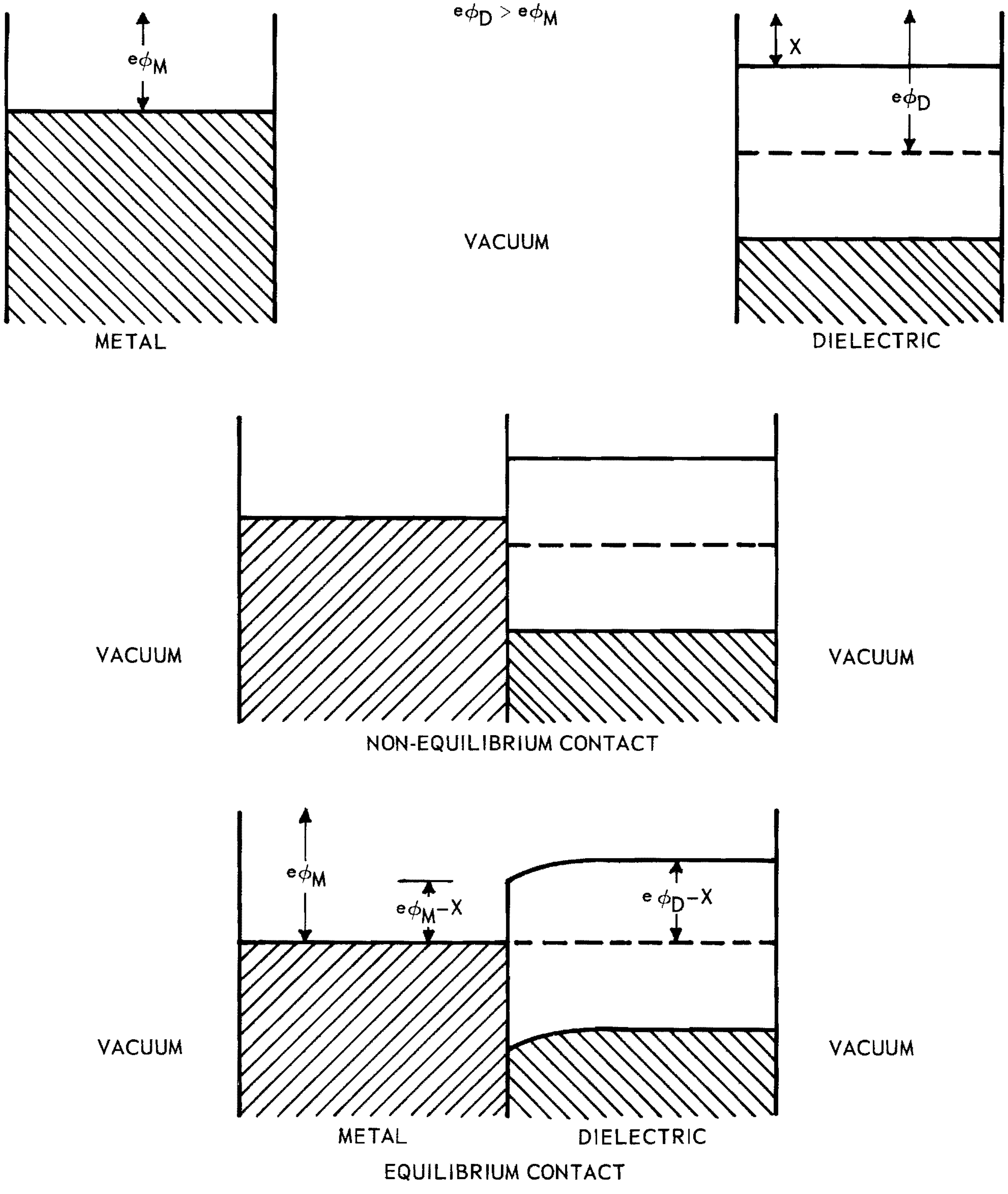

Figure 2. Potential Barrier at Metal-Dielectric Interface for $e\phi_D > e\phi_M$.

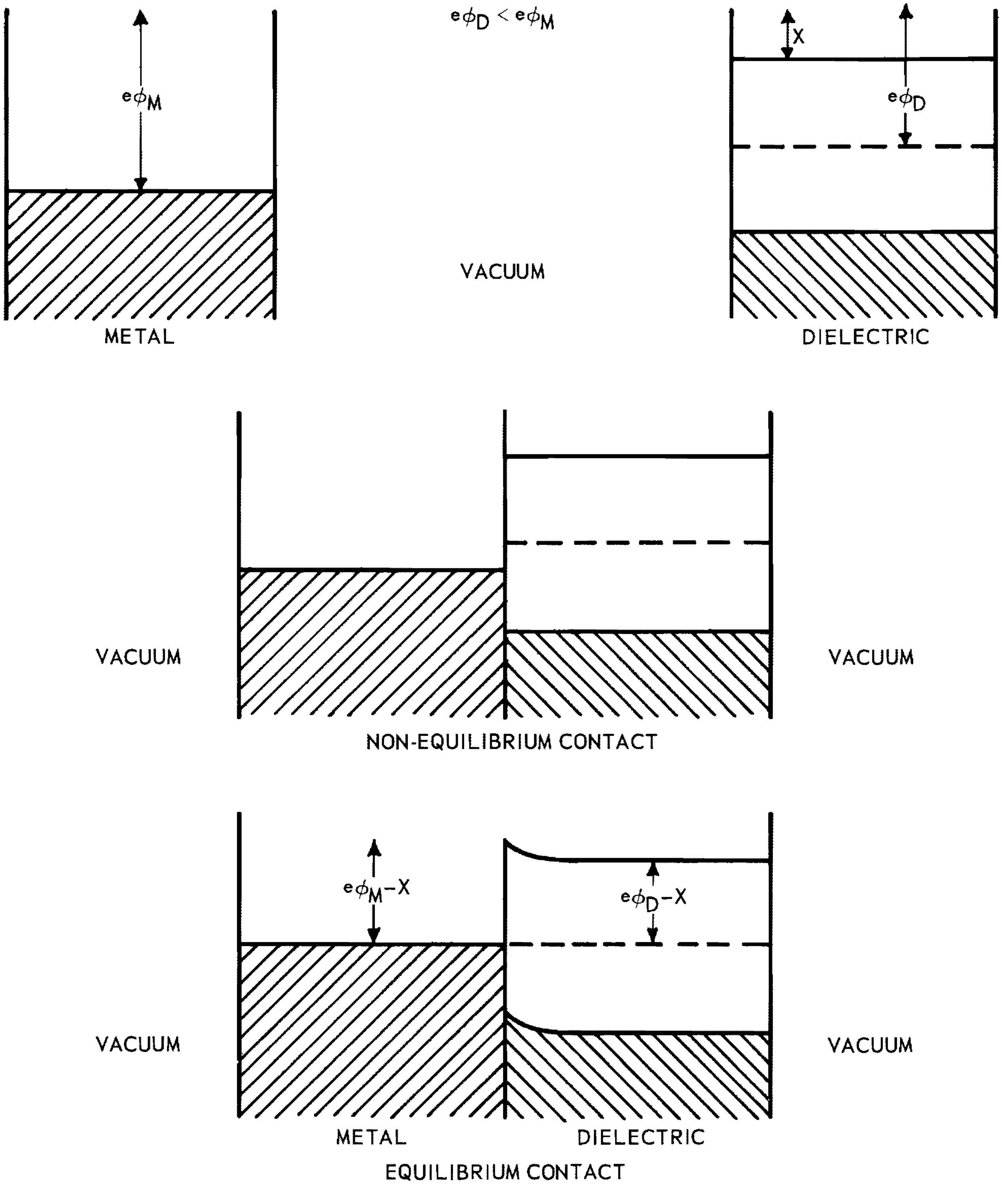

Figure 3. Potential Barrier at Metal-Dielectric Interface for $e\phi_D < e\phi_M$.

curvature to the conduction band and valence band of the dielectric. Again the barrier at the interface for electrons to get into the conduction band of the dielectric is $e\phi_M - \chi$. At large distances the conduction band of the dielectric is closer to the Fermi level and is separated in energy from the Fermi level by an amount $e\phi_D - \chi$. If the transition region is narrow there is a finite tunnel probability associated with an electron getting from the metal to the conduction band of the dielectric if the electron in the metal acquires an energy greater than $e\phi_D - \chi$ above the Fermi level.

As an example of the barrier presented to an electron going from a metal to a dielectric, assume a dielectric having a work function $e\phi_D = 4$ ev and an electron affinity of $\chi = 0.8$ ev. Then Table 1 gives a maximum and minimum value for the potential barrier for the electron in going from different metals to the dielectric. This table shows the desirability of using metal electrodes with a wide variation in work function.

As the actual experiment is concerned with a sandwich of a dielectric between two metal electrodes, the possibility exists of the transition layer going from one electrode to the other. Figure 4 shows this possibility for the three alternatives of the relative magnitude of $e\phi_M$ compared to $e\phi_D$. The conditions shown in Figure 4 will become apparent as the thickness of the dielectric is decreased. Consequently, a different potential barrier should be observed with decreasing film thickness. In addition, no mention has been made of the effect of an applied electric field across the dielectric. The effect of this applied field will be to increase the probability of the electron being able to penetrate the barrier by the tunnel effect. This effect has been treated by a number of investigators and the result of the

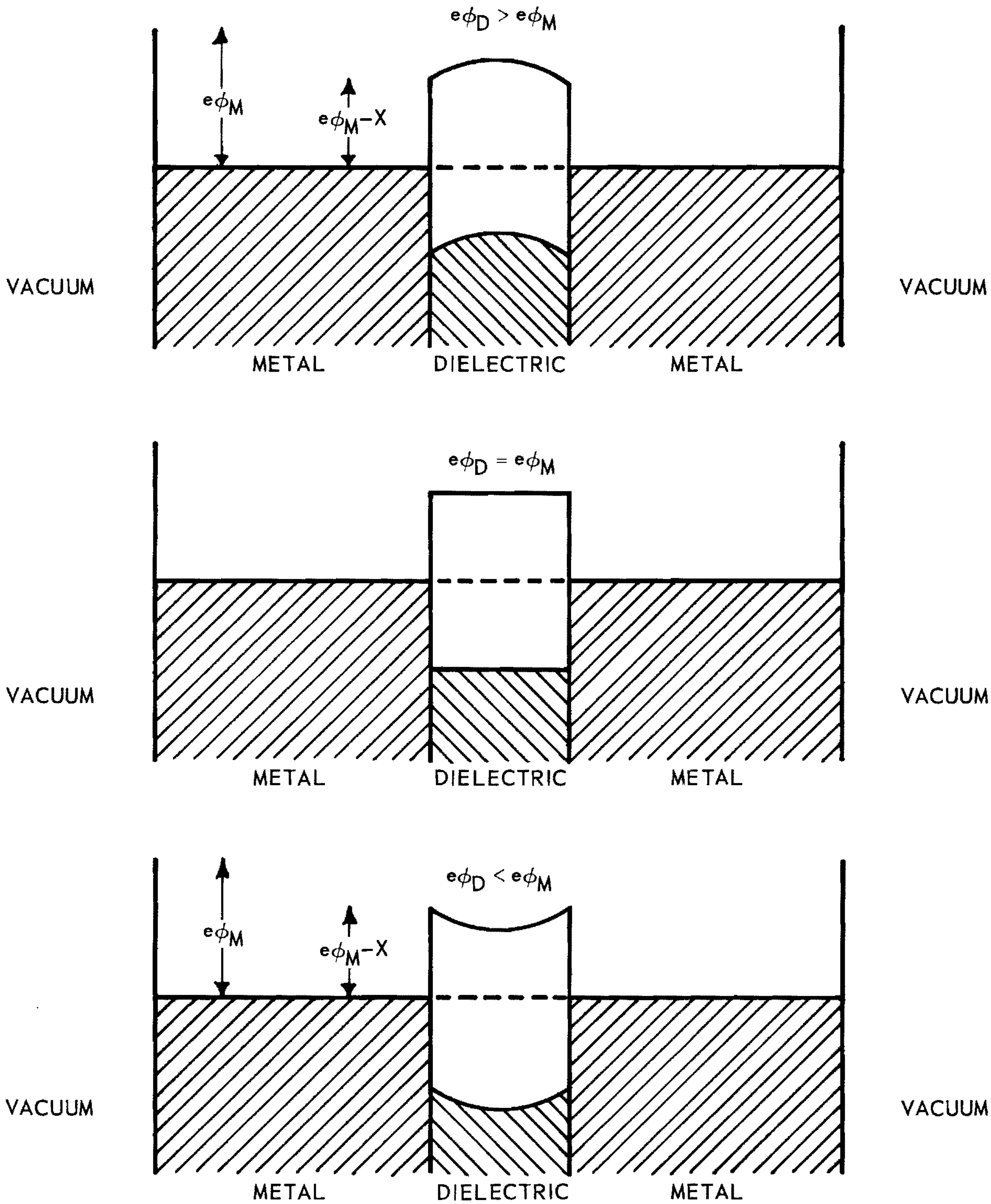

Figure 4. Comparison of Potential Distribution in Thin-Film Dielectric for Different Metal Contacts.

modification of the barrier by the applied field will be discussed when an analysis of actual results is given.

TABLE 1

DEPENDENCE OF ELECTRONIC POTENTIAL BARRIER
ON METAL ELECTRODE WORK FUNCTION

$e\phi_D$	χ	$e\phi_M$	$e\phi$ Min	$e\phi$ Max
4 ev	0.8 ev	5.0 ev	3.2 ev	4.2 ev
		4.8	3.2	4.0
		4.6	3.2	3.8
		4.4	3.2	3.6
		4.2	3.2	3.4
		4.0	3.2	3.2
		3.8	3.0	3.2
		3.6	2.8	3.2
		3.4	2.6	3.2
		3.2	2.4	3.2
		3.0	2.2	3.2

Some attempt has been made in the preceding discussion to present a qualitative model for the potential barrier to be anticipated with metal-dielectric interfaces. The next topic to discuss is the dependence of the photoelectric process on the potential barrier.

A sample is made of a sandwich of an insulator between two metals. An optical window is made in one metal electrode by either masking a section of the dielectric during formation of the metal electrode or making the electrode thin enough to be semi-transparent to the incident radiation. Light from a monochromator is allowed to illuminate the face of the insulator through the slit. Some fraction of this light passes through the insulator and into Metal I, there to be absorbed and create photoelectrons. In turn, some portion of the photoelectrons formed will move back through the interface and the insulator, and thence pass into Metal II. The passage of these electrons from Metal I to Metal II constitutes an electric current, and this current may be detected and measured with suitable external circuitry. An expression for the quantum yield Y, the number of electrons per incident photon that are photo-emitted from Metal I and subsequently arrive in Metal II must be found. The expression should be sufficiently general so that the experimental data can be used to determine something about the potential energy barrier shape from the derived expression.

For our purposes, a photoelectron is an electron that absorbs a photon and leaves Metal I with a positive x-component of velocity v_x such that $1/2mv_x^2 \geqq e\phi$, where $e\phi$ is the maximum of the barrier potential. The analytical problem consists of six parts: (1) transmission of light through the insulator; (2) absorption of photons by electrons in Metal I; (3) propagation of the electrons through Metal I to Interface I; (4) passage of the electrons through the barrier at the interface; (5) propagation of the electrons through the insulator and into Metal II; and (6) consideration of extraneous effects.

Theoretical Model

Let N(f) be the photon flux at frequency f in the incident light beam; the number of photons absorbed per unit area per second in Metal I will be given by

$$N_a(f,T) = A(f,T)N(f) \qquad (1)$$

where A(f,T) = the fraction of incident photons that are absorbed in Metal I, and T = absolute temperature. A(f,T) will be a rather complicated expression if multiple reflections and other optical effects are considered.

Of all the photons absorbed in Metal I, a certain fraction will be absorbed between x and x + dx. If this fraction is denoted by $g(x,f,T)dx$, then the number of photons absorbed between x and x + dx is given by

$$N_a'(x,f,T)dx = g(x,f,T)A(f,T)N(f)dx \qquad (2)$$

Then

$$\int_0^d g(x,f,T)dx = 1 \qquad (3)$$

in order that

$$\int_0^d N_a'(x)dx = N_a \qquad (4)$$

Now let: (1) $\sigma_t(x,f,T,v_x')dv_x'$ be the probability that the absorption of a photon will result in the production of an electron whose x-component of velocity lies between v_x' and $v_x' + dv_x'$; (2) $P(x,T,v_x',v_x)dv_x$ be the fraction of electrons having v_x' at x which reach Interface I with an x-component of velocities between v_x and $v_x + dv_x$; (3) $t(T, v_x)$ be the probability that an electron with an x-component of velocity v_x overcomes the potential barrier at Interface I; and (4) $q(T,v_x)$ be the fraction of the electrons which pass Interface I and reach the collector, Metal II. With the aid of this notation, we have

$$Y(f,T) = \frac{1}{N(f)} \int_0^d \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} q(T,v_x)t(T,v_x) \qquad (5)$$

$$P(x,T,v_x,v_x')\, \sigma_t(x,f,T,v_x')\, N_a'(x,f,T) \quad dv_x'dv_x dx$$

This expression can be written in an alternative form

$$Y = \frac{1}{N(f)} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} qt \int_{o}^{d} N_a' \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} P \, \sigma_t dv_x' dx dv_x \tag{6}$$

The integrals then have the following simple interpretations:

$$A dv_x = \left[\int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} P\sigma_t dv_x' \right] dv_x \tag{7}$$

and is the probability that the absorption of a photon at x will subsequently result in an electron arriving at Interface I with an x-component of velocity between v_x and $v_x + dv_x$. Hence,

$$B \, dv_x = \left[\int_o^d N_a' \, A \, dx \right] dv_x \tag{8}$$

is the total number of electrons per unit area per unit time which arrive at Interface I with an x-component of velocity between v_x and $v_x + dv_x$.

$$C = qt$$

is just the probability that an electron arriving at Interface I with velocity v_x will subsequently be found in Metal II. For thick specimens, no one electron is likely to make the complete journey from Metal I to Metal II. However, the current or the net flow of electrons in this direction will be directly related to the above expression by the fraction that the mean free path for the electron is of the dielectric thickness.

Assuming a mean free path equal to the thickness of the dielectric gives

$$\int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} CB \, dv_x$$

as the net flow of electrons into Metal II, and

$$Y = \frac{1}{N(f)} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} CB \, dv_x \tag{9}$$

is the desired quantum yield.

The limits of integration are based on the following argument. By definition, $1/2 \; Mv_x^2 \geqq e\phi$ at Interface I in order than an electron qualify for the photoemission process. This inequality means that either $v_x \geqq \left(\frac{2e\phi}{m}\right)^{1/2}$ or $v_x \leqq -\left(\frac{2e\phi}{m}\right)^{1/2}$. The first case obviously qualifies for the photoemission process. In the second case, however, it is reasonable to assume that in order for an electron with $v_x \leqq -\left(\frac{2e\phi}{m}\right)^{1/2}$ eventually to arrive at Interface I with $v_x \geqq \left(\frac{2e\phi}{m}\right)^{1/2}$, it must have undergone a sufficiently large number of collisions to be thermalized; hence, even though it may penetrate the barrier and contribute to the measured current, it cannot be included in Y. Thus, the v_x integration is over $v_x \geqq \left(\frac{2e\phi}{m}\right)^{1/2}$. A similar argument holds for the v_x' integration, if in addition it is assumed that the only collisions encountered by the electron in traversing the distance (d - x) are those which tend to decrease the x-component of velocity.

The expression for Y above does not contain any contribution due to thermal emission of electrons from Metal I, since the expression depends on the absorption of the photons. The expression for Y does allow for the distortion of the potential barrier by application of external fields, temperature changes, and other external parameters through the transmission probability $t(T,v_x)$.

The generality of the above expression for Y makes it applicable (to a limited extent) to other three-component samples in addition to the metal-insulator-metal sample we have been discussing. In fact, if we replace both the insulator and Metal II with a vacuum so that $q(T,v_x) = 1$, then we can write

$$Y = \frac{1}{N(f)} \int_{o}^{d} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} tP\sigma_t N_a' dv_x' dv_x dx \tag{10}$$

If the factor $q(x,f,T)$ in the expression for $N_a'(x,f,T)$ is considered to be a rapidly decreasing function of x in accordance with the exponential absorption of the radiation by the metal, an appreciable contribution to Y is obtained only from a surface region of depth Δ. If Δ is sufficiently small then the expression for Y collapses to

$$Y(T,f) = \frac{1}{N(f)} \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} t\sigma_t N_a' dv_x \tag{11}$$

or

$$Y(T,f) = K(f,T) \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} t\sigma_t dv_x \tag{12}$$

where

$$K(f,T) = \frac{N_a'(d,f,T)}{N(f)} = q(d,f,T)\ A(f,T) \tag{13}$$

Now Fowler[5] assumed that σ_t is just a constant k_o times the number of electrons with velocities in the x-direction (before absorption of a photon) characteristic of energies between $1/2m\ v_x^2 - hf$ and $1/2m\ v_x^2 - hf + dE$. This assumption results in

$$Y = Kk_o \int_{\left(\frac{2e\phi}{m}\right)^{1/2}}^{\infty} t \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(v_x, v_y, v_z) n(E) dv_z dv_y dv_x \tag{14}$$

where G is the density of states and n(E) is the Fermi function. This expression is identical with Fowler's result for clean metal surfaces. For values of f near the threshold frequency $f_o = \frac{W-E_f}{h}$, where E_f = Fermi energy, this reduces to

$$Y = P\ T^2 F\left[\frac{hf}{kT} - \frac{(e\phi - E_f)}{kT}\right] \tag{15}$$

Here $F(\mu)$ is the Fowler function, first elucidated by Fowler in the aforementioned paper; it is a rather complex function, but Fowler provided a series expansion and plot for log $F(\mu)$. Values of the Fowler function are tabulated in Table 6 as a convenience for the reader, and a theoretical plot is given in Figure 5. The coefficient P is a constant independent of f and T. If in the three-component sample only emission from the vicinity of the surface is considered then the simpler expression, Eq. 12, can be used and two possibilities exist.

First, Fowler's arguments can be retained and the only effect produced by the presence of the insulator is to change the height of the potential barrier by an amount χ, the electron affinity of the insulator. The following expression is obtained.

$$Y = P\ T^2 F\left[\frac{hf}{kT} - \frac{e\phi}{kT}\right] \tag{16}$$

Equation 16 offers a means for determining $e\phi$ by measuring Y as a function of T and plotting log Y/T^2 versus hf/kT. Provided Eq. 16 is valid, the resulting curve should be identical with a plot of $y = F(\mu)$ but shifted along the μ-axis by an amount $e\phi$. Thus by measuring this shift the value of $e\phi$ can be determined. Even in those cases where a good fit for the curves is not obtained an estimate of the height of the potential barrier may be possible.

The second possibility is to attempt to arrive at a reasonable expression for $t(T,v_x)$ and $\sigma_t(d,f,T,v_x)$ in terms of parameters characteristic of the potential barrier. Hopefully, then, the experimental data would determine these parameters, so that the shape of the potential barrier could be determined.

TABLE 2

VALUES OF FOWLER'S FUNCTION F(μ)

μ	$\log_{10}$	F(μ)	μ	$\log_{10}$	F(μ)
-8.0	+0.903	-3.475	+2.0	+0.301	+0.546
-6.0	0.778	-2.606	3.0	0.477	0.785
-5.0	0.699	-2.171	4.0	0.602	0.983
-4.0	0.602	-1.739	5.0	0.699	1.150
-3.0	0.477	-1.308	6.0	0.778	1.293
-2.5	0.398	-1.095	8.0	0.903	1.527
-2.0	0.301	-0.884	10.0	1.000	1.713
-1.5	0.176	-0.674	12.0	1.079	1.866
-1.0	0.000	-0.469	14.0	1.146	1.998
-0.5	-0.301	-0.268	16.0	1.204	2.113
-0.2	-0.699	-0.160	20.0	1.301	2.305
0.0	- ∞	-0.085	25.0	1.398	2.497
+0.2	-0.699	-0.015	30.0	1.477	2.655
0.4	-0.398	+0.055	35.0	1.544	2.788
0.6	-0.222	0.125	40.0	1.602	2.904
1.0	0.000	0.249	50.0	1.699	3.097
1.5	+0.176	0.400			

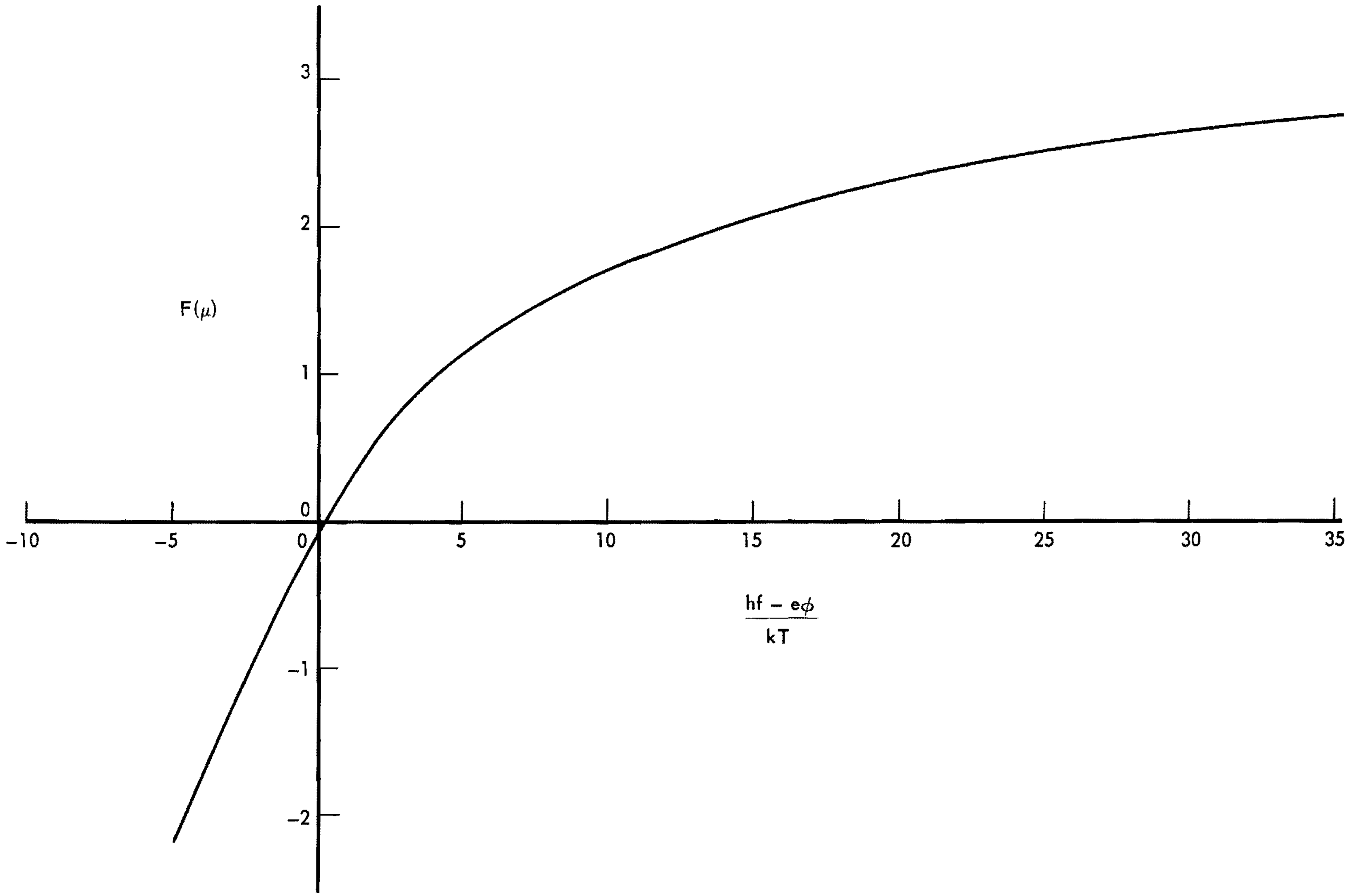

Figure 5. Theoretical Fowler Plot.

II. Experimental Procedures and Equipment

Sample Preparation

During the early stages of the work, samples were prepared in the form of thin films of Al_2O_3 between aluminum electrodes and in the form of single crystals of Al_2O_3 and MgO with evaporated aluminum electrodes and with electrodes applied in the form of silver paint. From a point of view of reproducible results on photoelectric emission data, these samples did not prove satisfactory as will be discussed later. Some thin film samples of TaN were obtained from Wright-Patterson and during the last few weeks films of TaN between tantalum electrodes were made at Georgia Tech with the use of the recently acquired electron beam equipment.

The thin films of Al_2O_3 between aluminum electrodes were prepared on glass substrates. The substrates were cleaned with chromic acid and acetone before placing them in the vacuum chamber. Aluminum wire (99.999% pure) was wrapped around a tungsten wire heating element. A vacuum of approximately 10^{-6} Torr was used during evaporations. A film of aluminum about 1 mm wide and 3 cm long was evaporated on the substrate. The oxide was formed by heating the metal and substrate in air at 180°C for about one week. A second aluminum evaporation provided a top electrode. This electrode was evaporated in the form of a 1 mm strip at right angles to the first strip. The thickness of the top electrode was kept thin so as to be translucent to incident light. The thickness of the oxide layer sandwich was determined by a measurement of low-frequency capacitance with an impedance bridge. The dielectric constant of the aluminum oxide was assumed to be 8 in the calculation of the thickness.

No corrections were made for the penetration of the metal electrode by the applied field[7].

Single crystals of Al_2O_3 and MgO used in some of the preliminary work were obtained from Semi Elements, Inc. These crystals were about 1/8" thick and approximately 3/4" x 3/4" square. In all configurations the applied electric field is parallel to the Poynting vector of the incident radiation.

The tantalum nitride films for which measurements are reported were obtained from Wright-Patterson[8]. During the last few weeks some tantalum nitride films between layers of tantalum were fabricated using the recently acquired electron beam equipment at Georgia Tech. A photograph of the electron beam equipment is shown in Figure 6. Tantalum was evaporated using the focused electron beam. The tantalum nitride was formed by sputtering tantalum in the presence of nitrogen. The second thin electrode of tantalum was then formed on the dielectric by use of the electron beam equipment.

Current vs Voltage Measurements

A previous report[9] submitted by Pyron and Nave has described a systematic study of voltage-current measurements on Al_2O_3 diode structures. Since thin film structures can vary depending on the conditions of formation, current-voltage characteristics were determined as a control on the electronic properties of the film before attempting to make photoelectric measurements. Experiments were made by applying a D.C. voltage to the diode and obtaining the resultant equilibrium current. The D.C. voltage was varied in steps from a voltage divider network. The

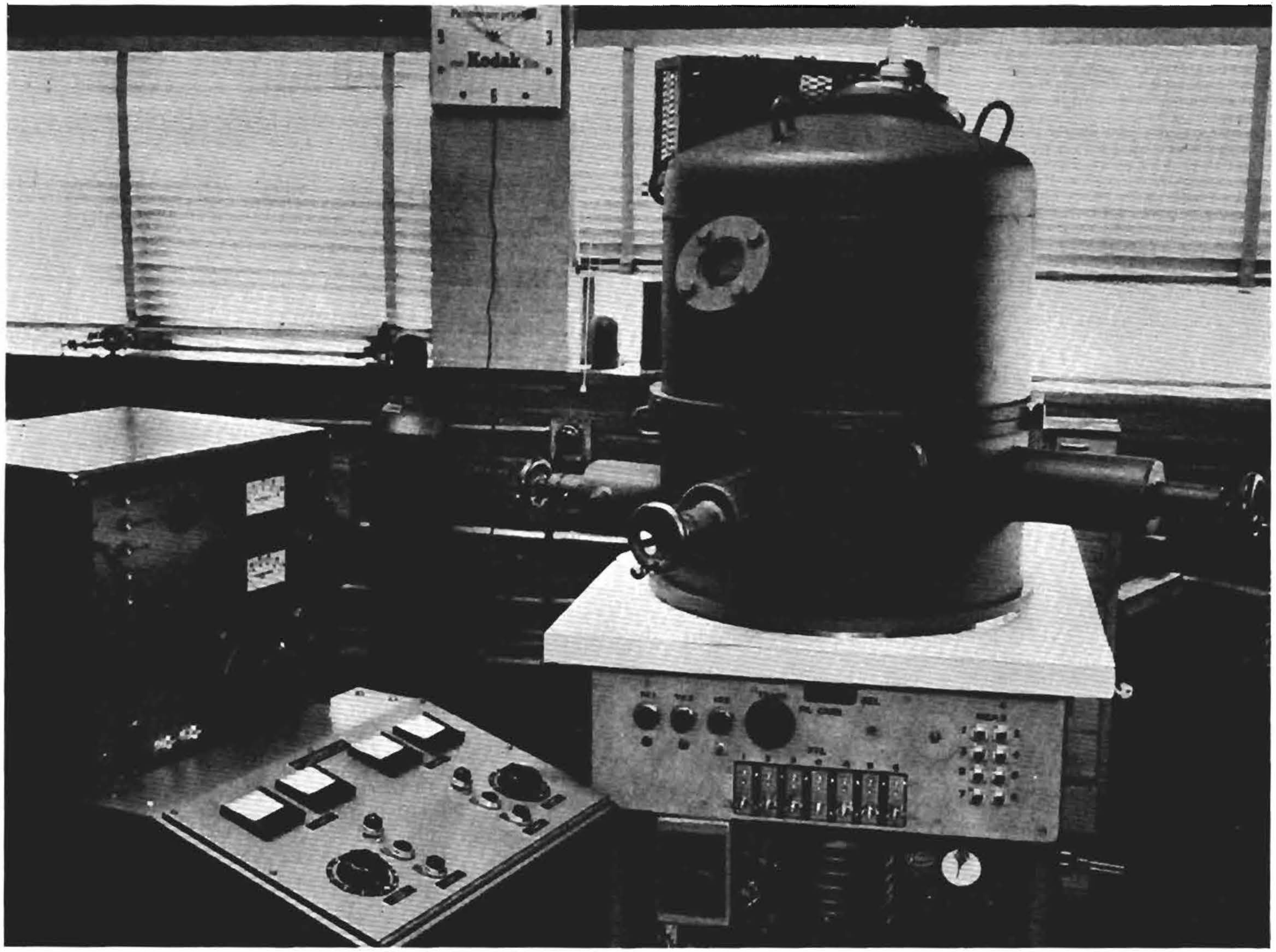

Figure 6. Electron Beam Equipment Used in Preparation of Thin-Film Samples.

voltage-current measurements were made both in air and in a vacuum of about 10^{-6} Torr. The same sample chamber used for photoelectric measurements in the near ultraviolet and visible region was used in making the current-voltage measurements.

Visible and Near Ultraviolet Measurements

The initial photoelectric emission measurements were attempted in the visible and near ultraviolet region of the spectrum. The wavelength range was from about 5000 Angstroms to 2500 Angstroms. A water-cooled 1000 watt AH-6 high pressure mercury arc was used as a source of continuous radiation for this wavelength interval. A Gaertner monochromator with quartz optics was used as the dispersing instrument. A calibrated RCA 935 phototube was used as a detector of the monochromatic intensity. An Applied Physics vibrating reed electrometer or a Keithley micro-microammeter was used as the instrument to measure the photoelectric current in the sample. Figure 7 shows a typical diagram of the experimental arrangement. Light from the AH-6 mercury arc impinges on the entrance slit of the Gaertner monochromator. The light is dispersed in the prism and is focused on the exit slit of the monochromator. The monochromatic light undergoes a double reflection and passes through a quartz window into the evacuated sample chamber. The light strikes the sample and the photo-current in the circuit is determined. The glass substrate on which the sample is formed is mechanically mounted on a block of teflon. A unique design of a glass to metal seal depicted in the diagram allowed a good vacuum inside the sample chamber while the leakage current was reduced to about 10^{-16} amperes. This seal consisted of a 1" O.D. Kovar to pyrex grade about 4" in length. The 1" Kovar was sealed into

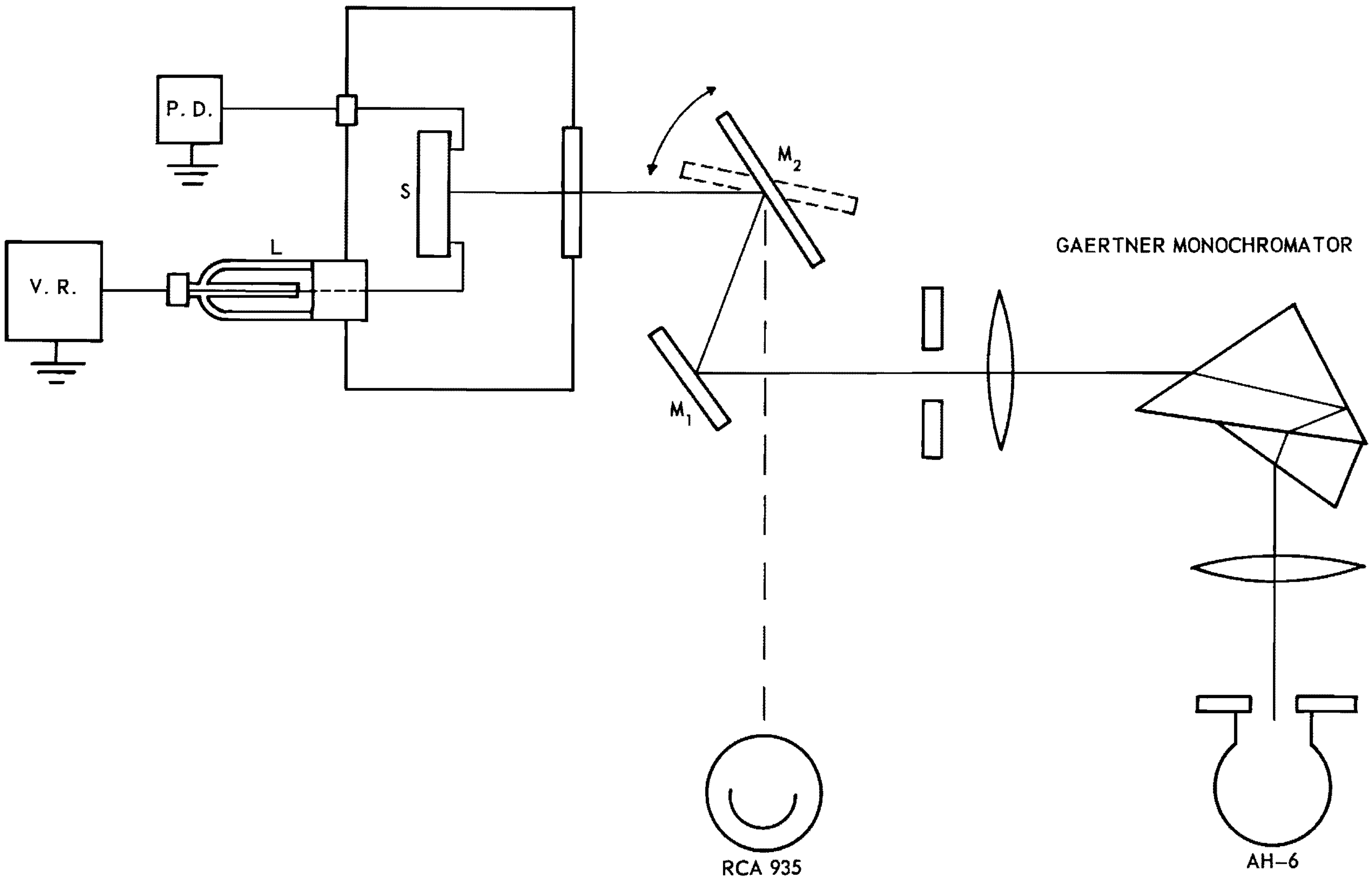

Figure 7. Experimental Arrangement for Visible and Near Ultraviolet Measurements.

the sample chamber. A ring seal was then made between the 1" pyrex and a 1/8" pyrex to Kovar graded seal. The 1/8" pyrex went into the sample chamber and one electrical lead from the sample was passed through the small pyrex tube and soldered to a brass plug on the end of the 1/8" Kovar. The brass plug made direct contact with the center electrode in the vibrating reed pre-amplifier head. No spurious effects were encountered from the use of Kovar to pyrex seals.

The second reflecting mirror after the light left the monochromator served a double purpose. The mirror could be rotated as indicated in the diagram. This rotation served as a shutter so that a direct measurement could be made of the comparison of the current in the sample with the light on as compared with the measurement with light off. Secondly, with proper rotation of the mirror the light could be directed to the 935 phototube for a measurement of the incident intensity.

The voltage applied across the dielectric could be changed in steps and reversed in direction by using a potential divider. This same divider was also used in taking current-voltage characteristics of the sample. The output voltage was calculated from a knowledge of the values of the resistors used and then measured by use of a Type K potentiometer circuit. The emf of the battery was recorded during the taking of data, and the voltage applied to the sample was calculated from the setting of the potential divider.

Several types of sample chambers were used during the course of the investigation. Although several different designs finally proved satisfactory, the chambers had many features in common and differed only in detail. In general, the sample chambers were large enough so that manual alignment of the sample could be easily accomplished prior to evacuation. A window to observe the sample in addition to the window used to illuminate the sample was found desirable. A high vacuum valve was found useful in isolating the vacuum system from the sample chamber. The complete optical path was enclosed to avoid the complications of room light. Only the chamber containing the sample was evacuated. A liquid nitrogen trap was found to be necessary between the diffusion pump and the sample chamber as the absence of the trap allowed sufficient back diffusion of gas ions to give an erratic background current in the photocurrent circuit. A pressure of about 10^{-6} Torr was maintained in the sample chamber while measurements were being made. The pressure was measured in a tube connected to the pumping lead at the entrance to the sample chamber. Electrostatic shielding was afforded by the use of either copper or brass for the construction of the sample chamber. The glass to metal seal previously described was completely enclosed in a metal housing. Figure 8 shows a photograph of the equipment used in the visible and near ultraviolet while Figure 9 shows a photograph of a sample chamber used for some of the measurements.

Vacuum Ultraviolet Measurements

During the course of the investigation the extension of the photoemission measurements to shorter wavelengths was found to be desirable. For this purpose a one meter normal incidence grating monochromator was used. Since wavelengths from approximately 900 Å to 3000 Å were to be used, the entire optical path was in a vacuum with no windows between the source and the sample. Figure 10 shows a diagram of the optical path. Light from a hydrogen discharge lamp passed through the entrance slit to the one-meter vacuum chamber. The light was dispersed by a reflection grating at close to normal incidence. The grating could be rotated through an o-ring seal. The monochromatic light passed through the exit slit into the housing containing the sample. When wavelengths shorter than 1900 Å were used, the light

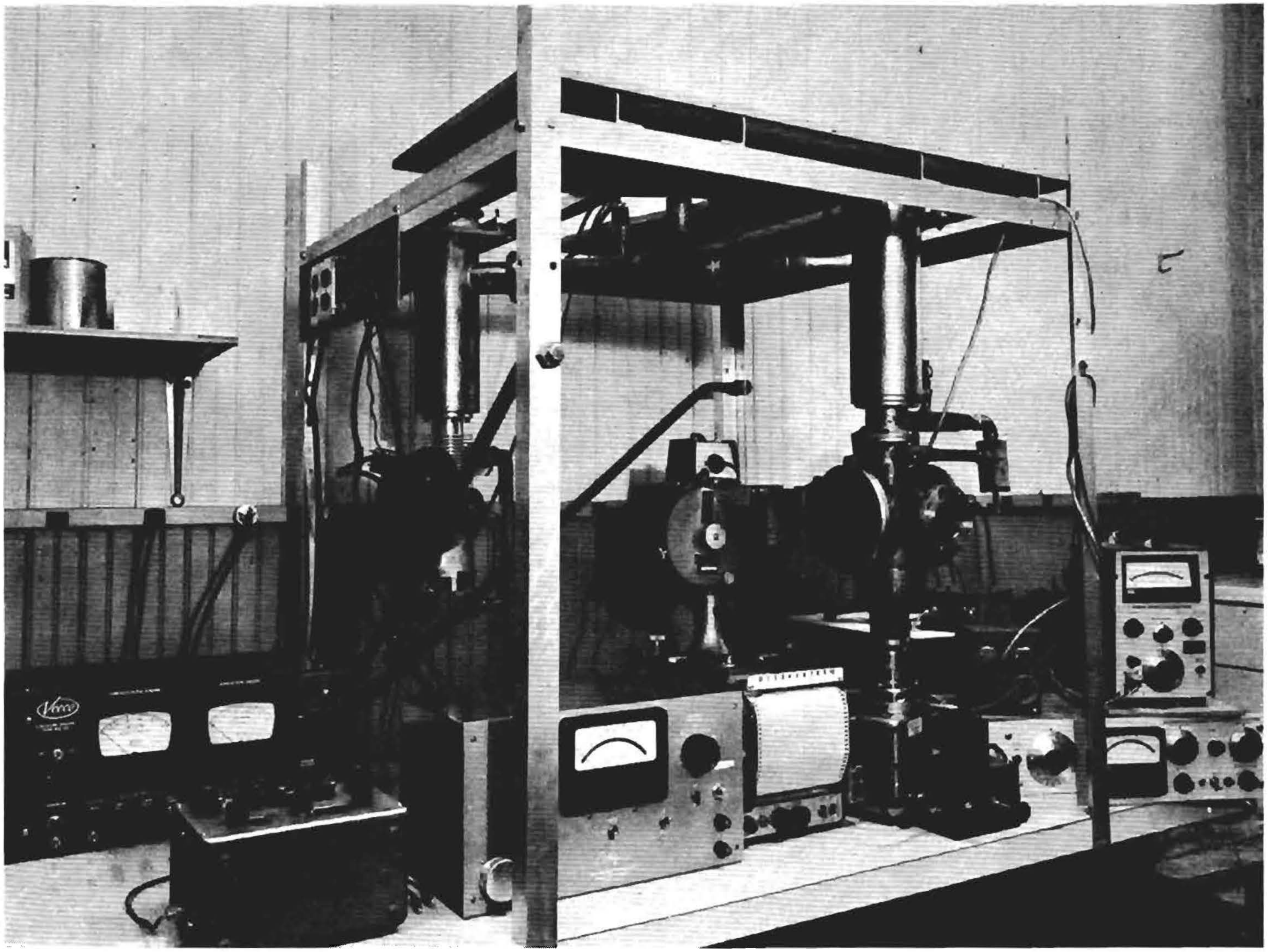

Figure 8. Equipment Used in Visible and Near Ultraviolet Measurements

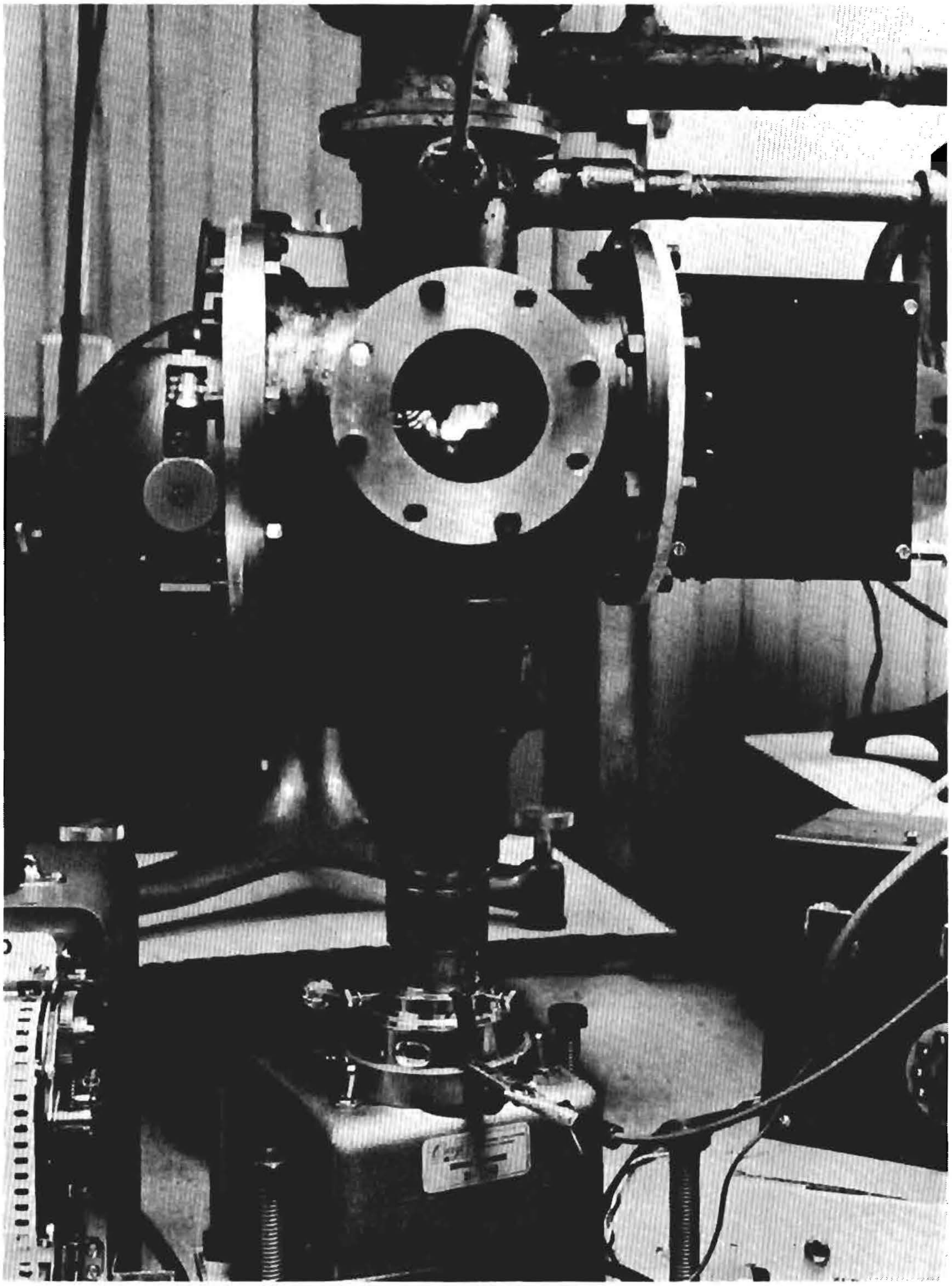

Figure 9. Sample Chamber Used in Visible and Near Ultraviolet Measurements.

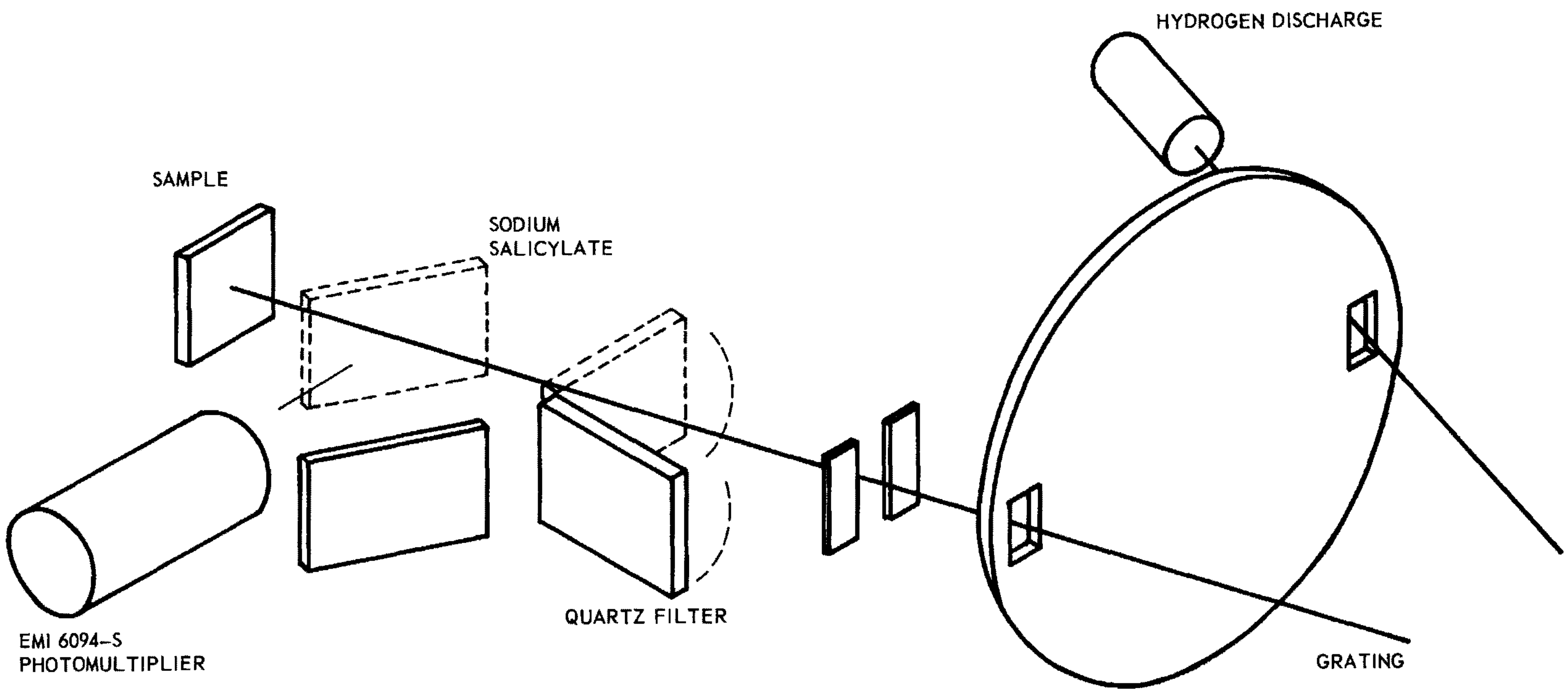

Figure 10. Optical Path in Vacuum Ultraviolet Measurements.

was allowed to strike the sample without passing through any windows. For wavelengths larger than 1900 Å, a quartz plate was used between the exit slit and the sample to prevent 2nd order short wavelength light from complicating the measurements. The incident intensity was monitored by putting a plate coated with sodium salicylate in the beam. The luminescence from the sodium salicylate was viewed through a lucite window by a 6094-S EMI photomultiplier tube. The photocurrent in the sample was measured by a vibrating reed electrometer. Figure 11 shows a photograph of the experimental arrangement, while Figure 12 is a photographic closeup of the light source and sample chamber.

Some preliminary measurements were made on the reflectivity of a TaN film on a quartz substrate in the vacuum ultraviolet so that the photoelectric yield could be corrected for the reflected intensity. These reflection measurements were made on a companion instrument to the one described above. The sample chamber is slightly different so that both the incident light and the reflected light could be determined. Figure 13 shows a photograph of the instrument used in these measurements.

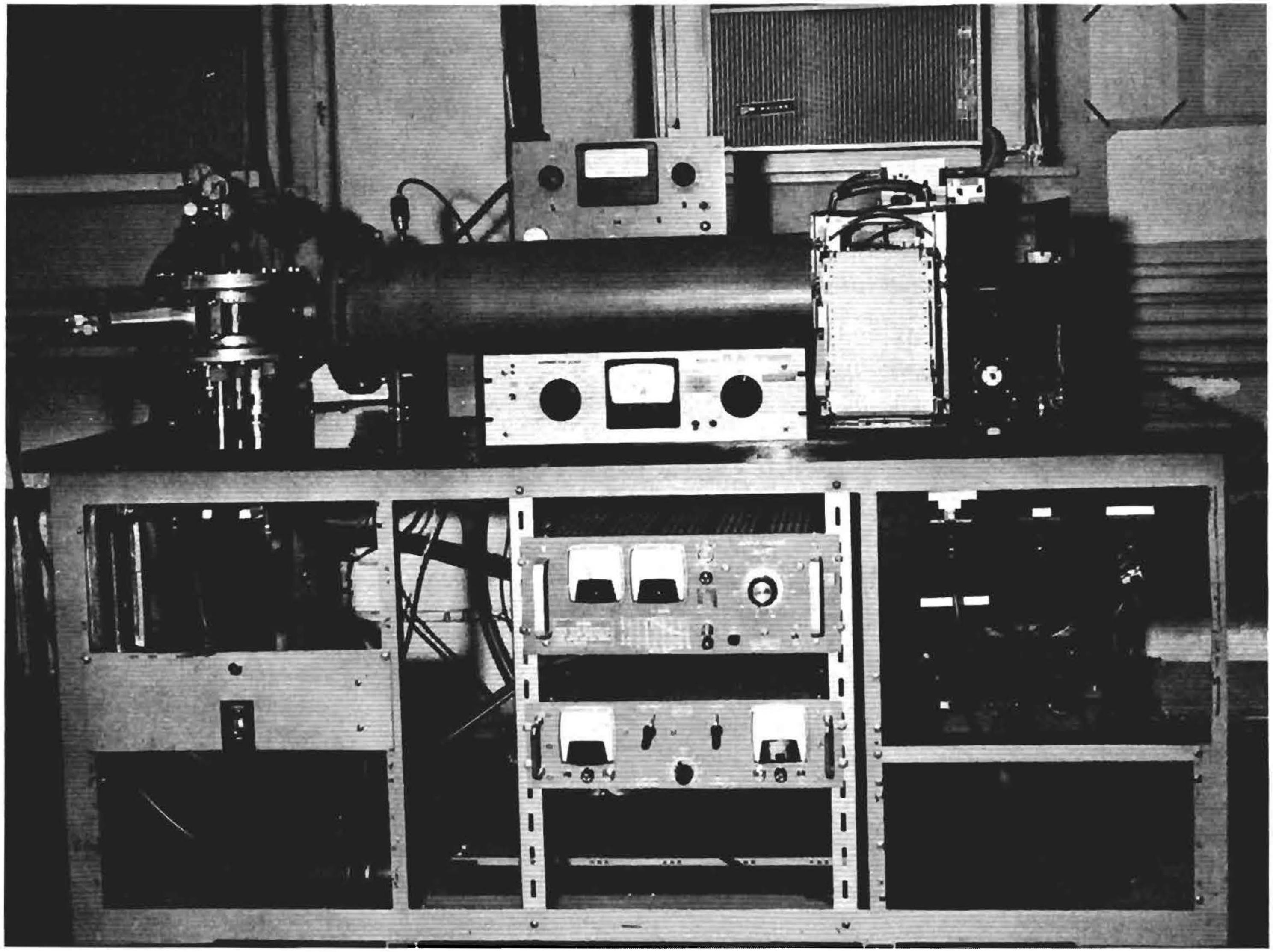

Figure 11. Equipment Used in Vacuum Ultraviolet Emission Measurements.

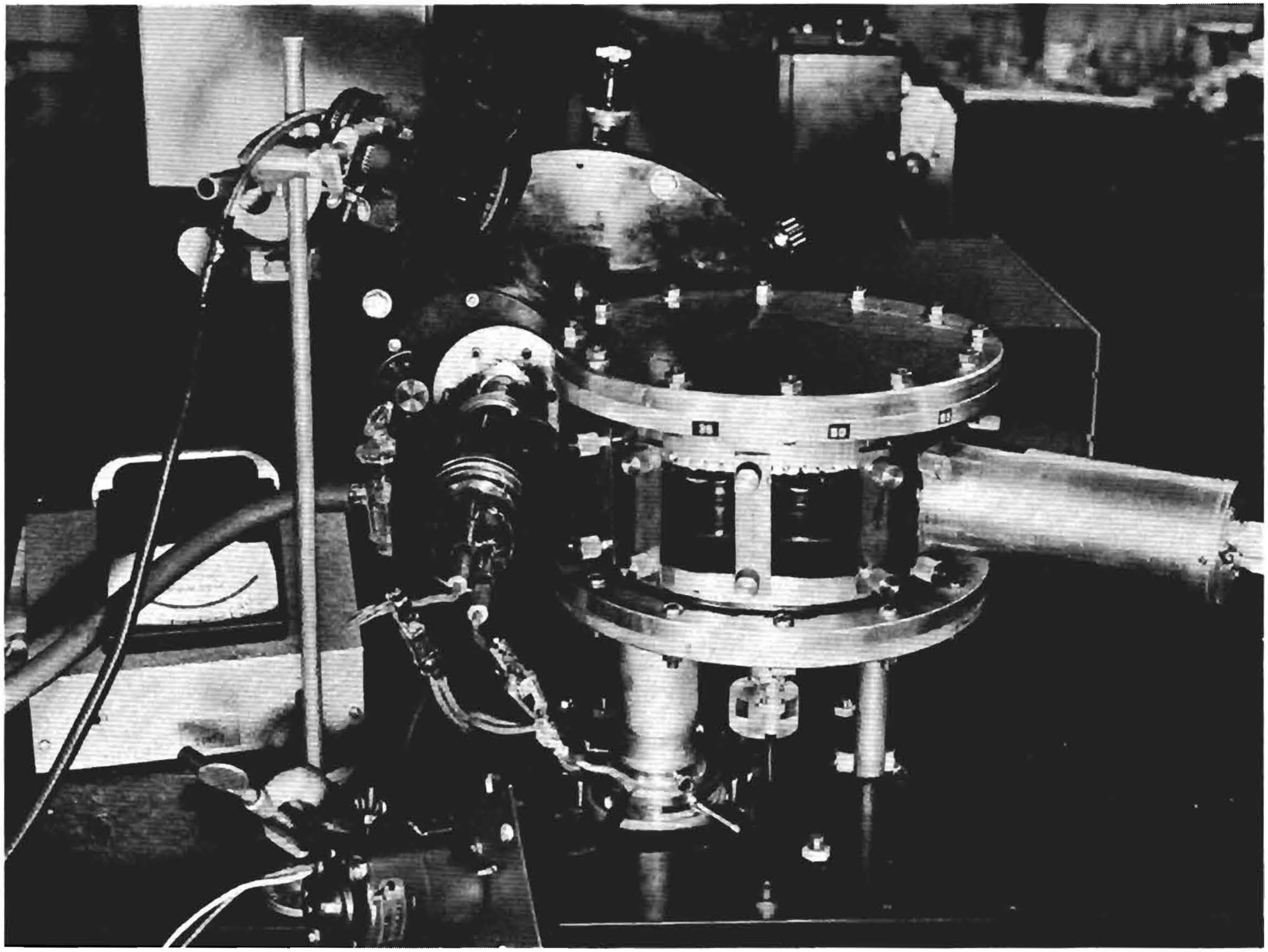

Figure 12. Sample Chamber and Light Source Used in Vacuum Ultraviolet Emission Measurements.

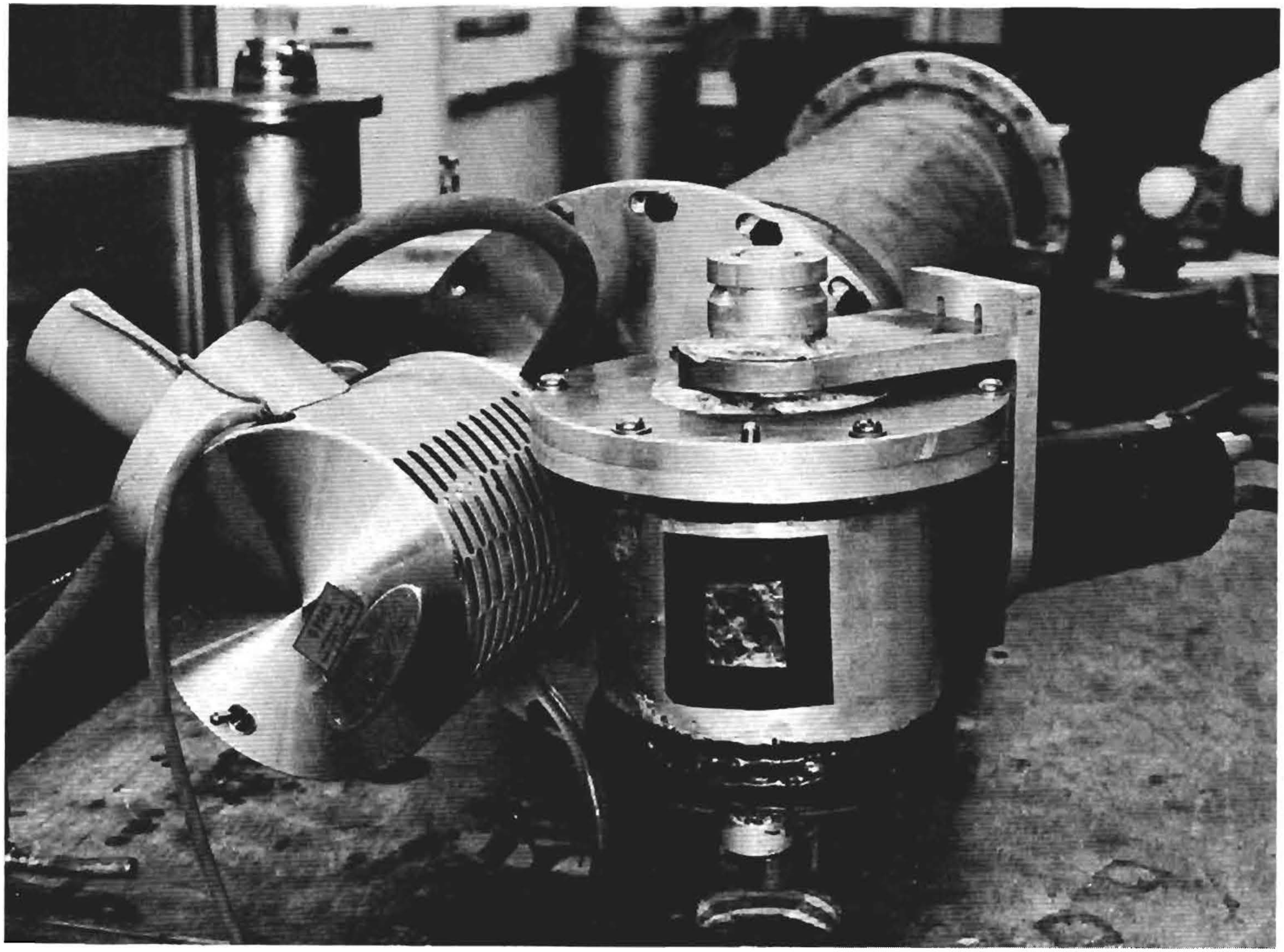

Figure 13. Sample Chamber and Light Source Used in Vacuum Ultraviolet Reflection Measurements.

III. Results

Current vs Voltage Characteristics on Al_2O_3 Films

The electrode-dielectric configuration used in these experiments is the same as that used in the tunnel diode structures. Although the present investigation is not directly concerned with the measurement of current-voltage characteristics, a knowledge of these characteristics for the films under investigation by the photoelectric emission process is desirable for later application of the photoelectric data to calculate the probability of tunneling. Card and Sahba[10] have reported observations on Al_2O_3 tunnel diodes for which the data is presented on a Fowler-Nordheim[11] plot of log $(\frac{J}{E^2})$ vs $\frac{1}{E}$ where J is the current density and E is the electric field. The theoretical Fowler-Nordheim plot should yield a straight line with a negative slope. When the tunnel emission has its origin from traps the slope of the line corresponds to the trap depth.

The data taken for current vs voltage characteristics of the Al_2O_3 films prepared for the photoemission studies did not show the typical tunnel characteristics. The preparation of the films was done by oxidation in air at an elevated temperature. Results for four typical films are shown plotted in Figure 14. These films were approximately 70 Å thick as measured by capacitance method. The junction area was approximately 1 mm x 1 mm. The curves are not straight lines and have a positive slope. However, the particular problem of concern to the photoelectric process is the high value of the dark current. Consequently, the observation of a photocurrent which is probably a factor of 10^6 to 10^9 below the dark current could not be made. From the point of view of the feasibility of observing a photoelectric effect, the

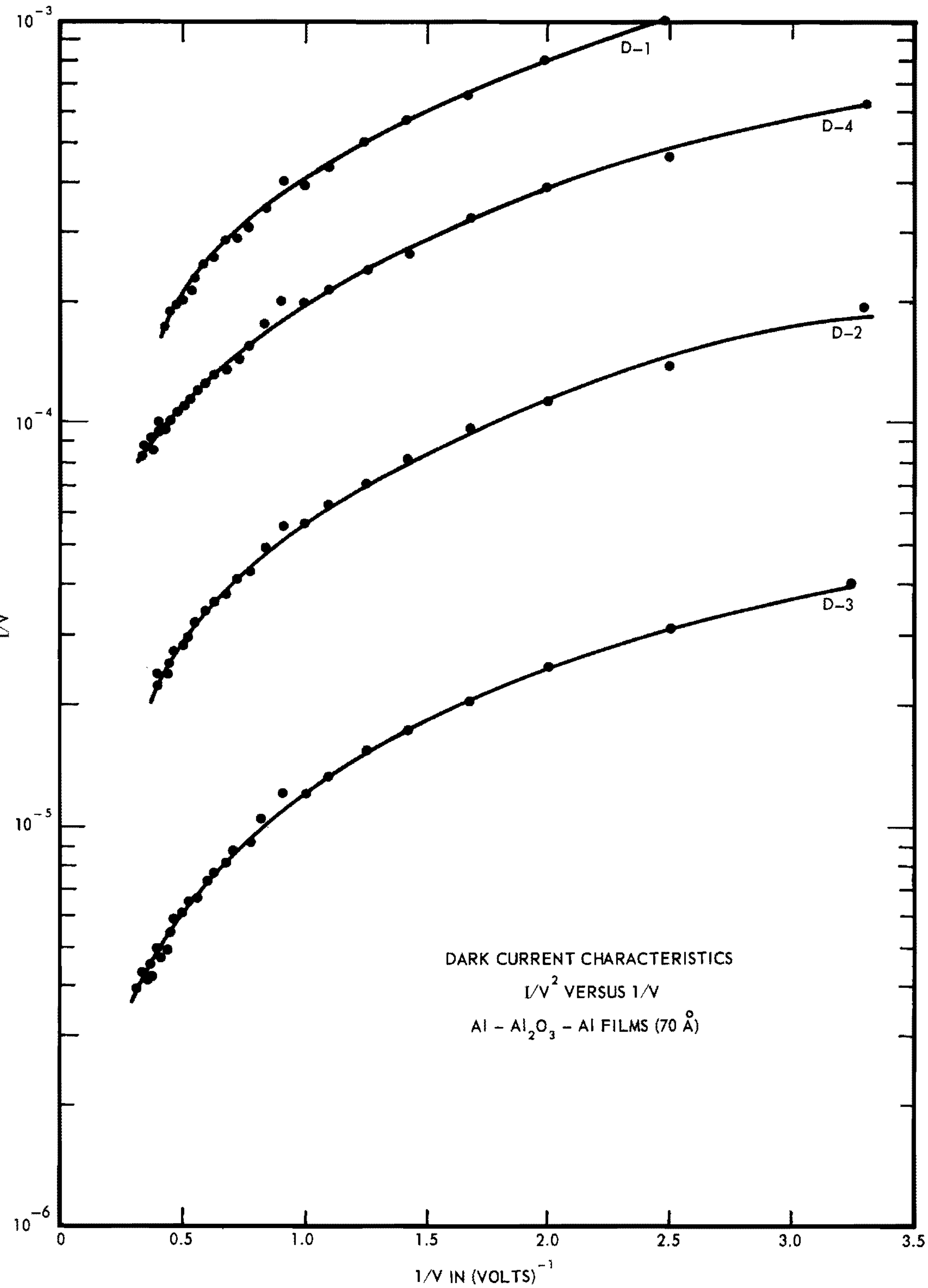

Figure 14. Fowler-Nordheim Plot for Al-Al_2O_3-Al Sandwich.

criterion is the magnitude of the current for the diodes rather than an analysis of the shapes of the current vs voltage curves. Figure 15 shows current vs voltage characteristics for another film. Again the principal feature is the high current for a relatively low applied voltage. From a knowledge of these current-voltage measurements, the experimental determination of the photoelectric contribution is very difficult.

Visible and Near Ultraviolet Photoelectric Measurements on Al_2O_3

From the above discussion the obvious conclusion is that the application of a voltage across the film results in such an alteration of the potential barrier shown in Figure 4 that the discussion in terms of this simple picture is no longer valid. So, unfortunately, the use of a potential barrier altered by the presence of the external field does not assist the experimental aspects of the problem.

Although no reproducible results were obtained for photoelectric emission from Al-Al_2O_3-Al films in the visible and near ultraviolet, an analysis of the failure showed the direction which did yield some preliminary results. Since the magnitude of the photocurrent must be increased with respect to the dark current, either the photoelectric yield must be increased or the dark current decreased. Both of these avenues were followed. An attempt was made to increase the photoelectric yield by going to shorter wavelengths (especially the vacuum ultraviolet region between 2000 Å and 900 Å). The background current was decreased by decreasing the applied field and using an open circuit measurement technique. Since these measurements were made on Ta-TaN-Ta samples, the results will be described in a discussion of these films.

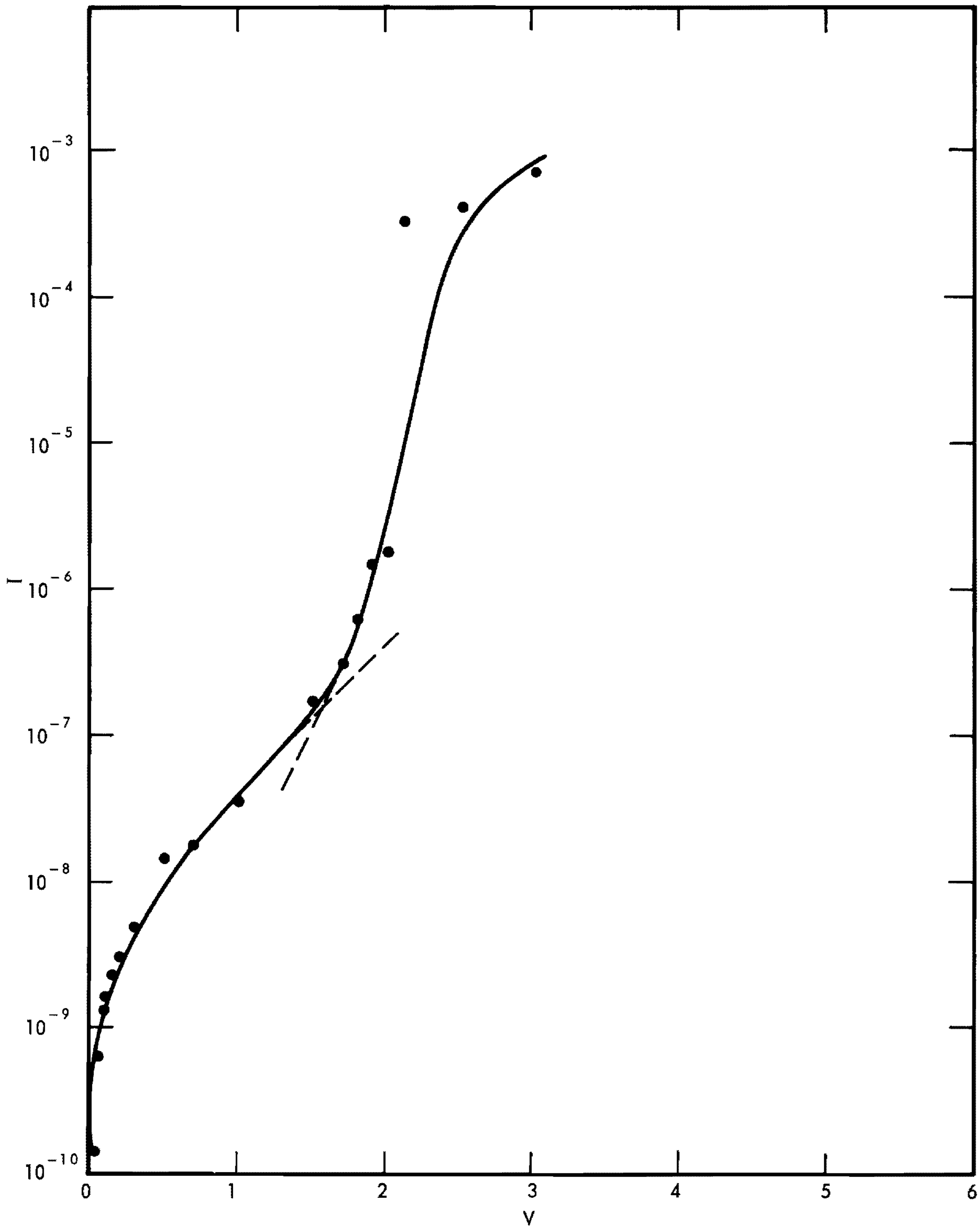

Figure 15. Current vs Applied Voltage for $Al-Al_2O_3-Al$ Sandwich.

Current-Voltage Characteristics of Ta-TaN-Ta Films

These films, as mentioned previously, were supplied by Mr. John M. Blasingame, Jr. of Wright-Patterson AFB. The film thickness of the TaN had been estimated at 400 Å. Figure 16 shows a Fowler-Nordheim plot for these films. The film designated as T-2-1 is the only film showing a tunnel characteristic at high fields. Again the currents were too high to expect to obtain photoelectric data. As a result of the previous experience with the Al-Al_2O_3-Al structures, a difference approach was used on the photoelectric data.

Photoelectric Data on Ta-TaN-Ta Films

The use of vacuum ultraviolet was deemed desirable to increase the photoelectric yield. The vacuum ultraviolet instrumentation has been previously described and depicted in Figure 10. The electrical connections to the sample were the same as in Figure 7 with one major exception. One contact to the sample was left open and separated from the tantalum electrode by approximately 1 mm. Thus, with 1 volt applied in the circuit, the field across the sample was decreased appreciably as most of the voltage drop was across the 1-mm gap instead of the 400-Å film. A circuit of this type immediately raises the question of the role of space charge. However, if the incident radiation produces a space charge region, a time dependence will be associated with the current. The measurements were made with currents sufficiently low (10^{-14} to 10^{-16} amps) that this effect was present to a noticeable extent. A time dependence was noted if the currents were allowed to become too large.

Figure 17A shows the photoelectric yield as a function of hf in electron volts between 4 ev and 10 ev. Figure 17B shows an extension of the same data

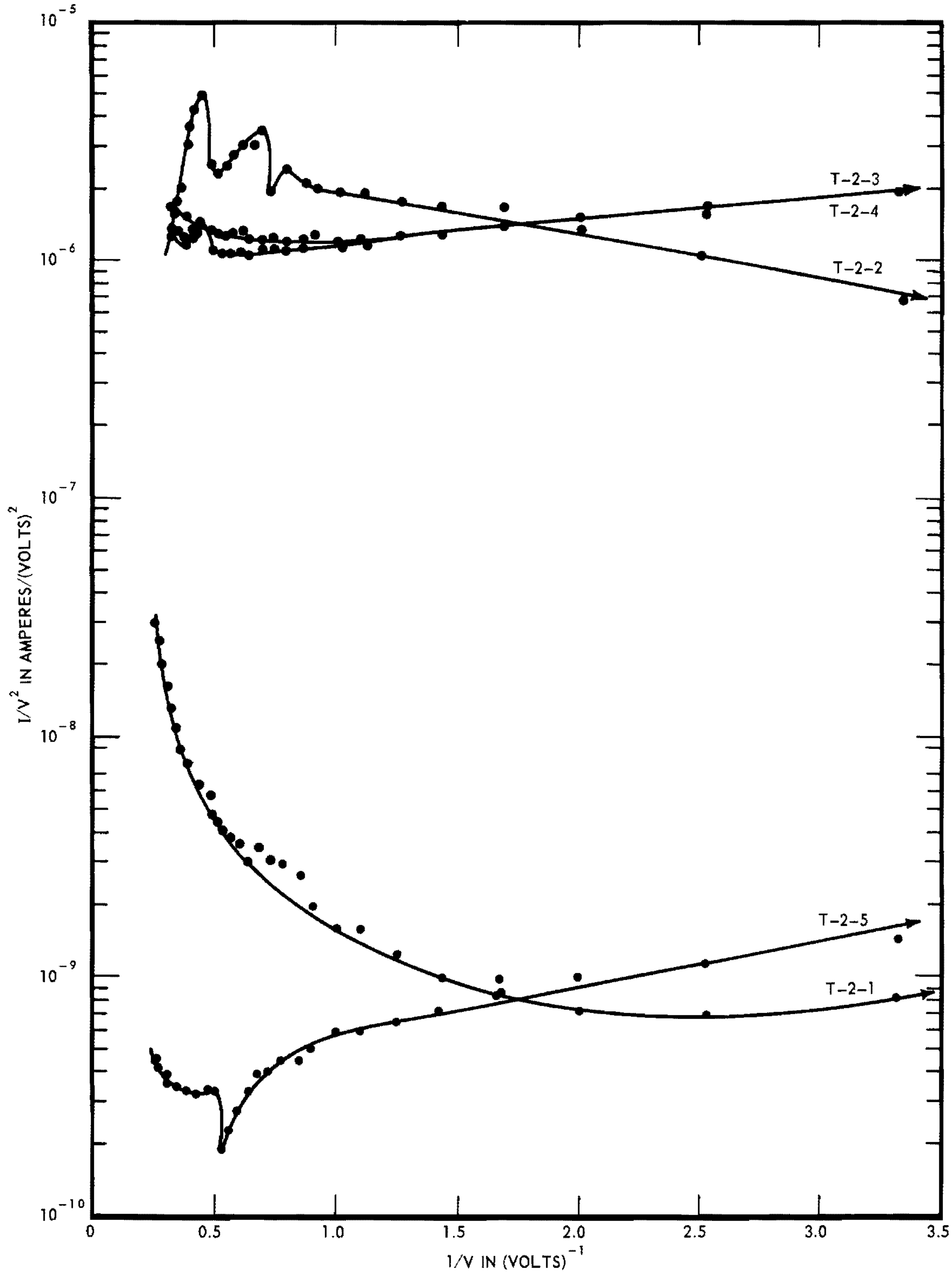

Figure 16. Fowler-Nordheim Plot for Five Separate Ta-TaN-Ta Diodes.

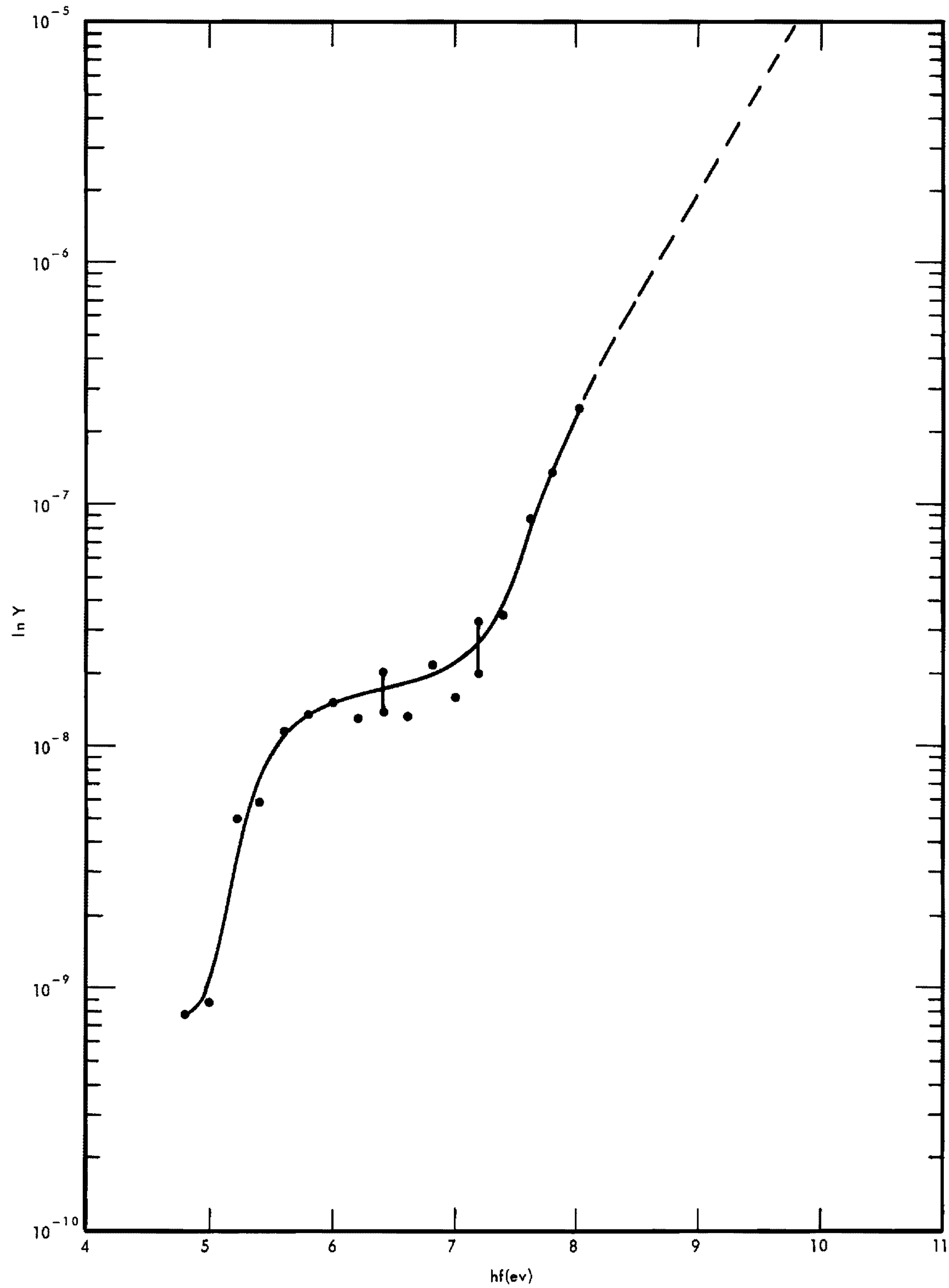

Figure 17A. Relative Photoelectric Sensitivity vs hf in Electron Volts for Ta-TaN-Ta Sandwich.

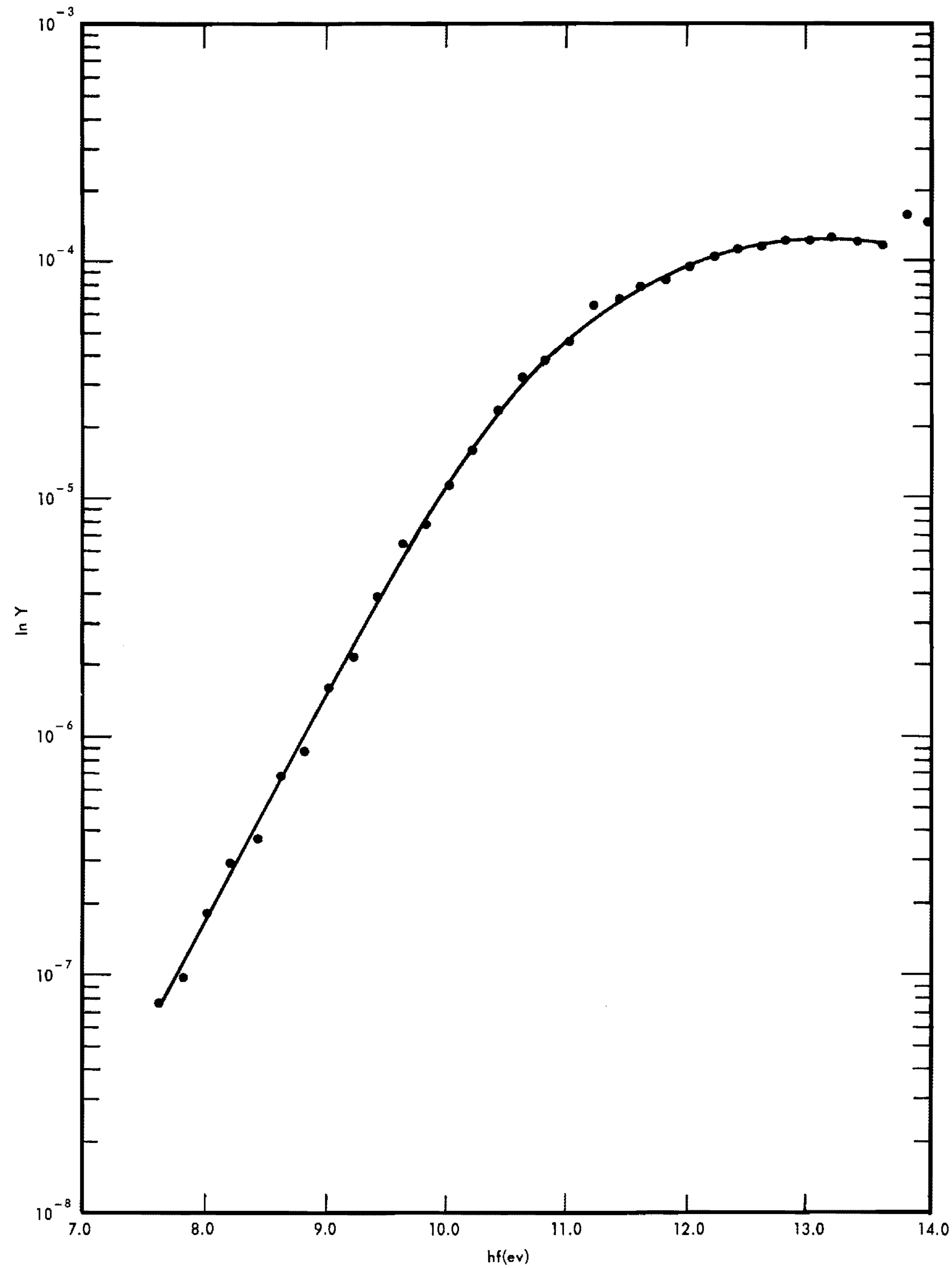

Figure 17B. Relative Photoelectric Sensitivity vs hf in Electron Volts for Ta-TaN-Ta Sandwich (Continued) to 14 ev of incident photon energy. From the shape of the curves given a simple Fowler type theory is seen not to be applicable. A threshold seems to take place at approximately 5 ev and a second threshold at about 7 ev. Probably both of these processes are intimately related to traps in the TaN dielectric. These results also confirm the preliminary observations of Ullman[12] who found a qualitative threshold at the 2537 Å line of mercury for photoeffects in a TaN film.

The density of traps contributing to the photoeffect was estimated by the following experiment. The sandwich had a field applied in the dark. A background current was measured using the rate of charge method. A light was then allowed to illuminate the sample. A sudden charge release was measured on the electrometer to be approximately 10^{-12} coulombs. This charge is equivalent to 10^7 electrons. If the electrons were uniformly distributed through the volume of the TaN (400 Å x 1 mm x 1 mm), then the estimated trap density is about 10^{15} cm^{-3}.

Reflectivity of TaN in Vacuum Ultraviolet

Since the photoelectric yield presented in Figures 17A and 17B is representative of electrons released per photon absorbed the yield would be inaccurate if the reflectivity of the sample changed over the wavelength interval. A sample of TaN sputtered on a quartz substrate was supplied by Mr. Blasingame of Wright-Patterson and the reflectivity was measured at approximately 45° angle of incidence over the interval of 4 ev to 17 ev. The results are shown in Figure 18. Although some structure is evident, the correction of the data will not change the shape appreciably. Figure 18 shows that the reflectivity is constant to within a factor of 2 over the entire interval in which a factor of 10^5 in the yield was observed. In addition,

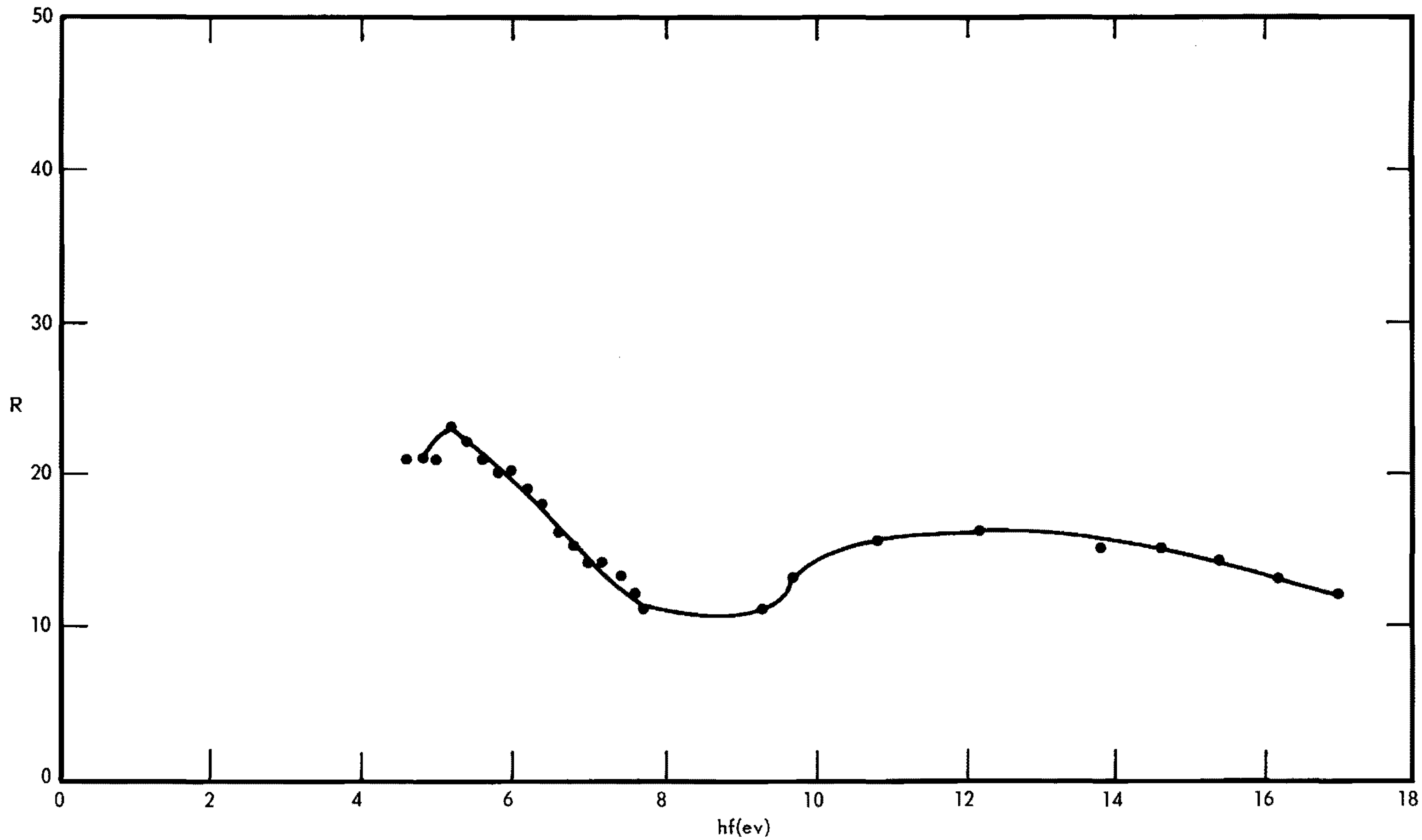

Figure 18. Reflectivity of TaN in the Near Ultraviolet and Vacuum Ultraviolet Region

the transmission of the first tantalum film must be measured to determine if any structure is present.

IV. Conclusions and Recommendations

The principal contributions of this work are thought to be: (1) the theoretical analysis on a simple model of the observation of a photoelectric emission from a metal surface into a dielectric; (2) the development of the open circuit technique in making these photoelectric measurements; and (3) the limited observations on TaN which include:

a) observation of two thresholds for photoelectric processes at about 5 and 7 ev,

b) identification of the processes as being associated with traps in the dielectric,

c) the estimate of trap densities to be about $10^{15} cm^{-3}$ for these particular processes.

Recommendations for continued work in this area include the following:

1) The use of the open circuit technique with various electrode materials in the visible region to see if results similar to Table I can be obtained.

2) An analysis of the photoconductive processes in the TaN films by measuring currents transverse to the Poynting vector. These measurements would tend to minimize the electrode effect.

3) An accurate determination of the optical constants of TaN films so that both reflectivity and absorption constants are known over the wavelength region of interest.

4) Finally, the temperature dependence of these effects should be measured.

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