SCHOTTKY EMISSION
THROUGH THIN ALUMINUM-OXIDE FILMS

by

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SCHOTTKY EMISSION THROUGH THIN ALUMINUM-OXIDE FILMS

INTRODUCTION

During the past two years considerable interest has developed in the studies of electronic phenomena in metals and insulators and in current transfer processes where electrons pass through thin layers of insulating material by one or more of several methods. While the work in this area is in its early stages and the theoretical background is quite undeveloped, there is promise that an adequate understanding of the underlying phenomena may unify and serve to strengthen the understanding of other related phenomena such as thermionic emission, high-field emission, and metal-to-metal contacts in electric circuits. In addition, the feasibility of a new class of devices operating on these principles have already been demonstrated.

At present the lack of techniques suitable for fabricating structures that demonstrate the phenomena is a serious limitation as is also an incomplete knowledge of the pertinent properties of the metals and insulators from which these structures are built. In general, the successful structures reported in the literature have been fabricated using high
and ultra-high vacuum techniques and from materials of the maximum obtainable purity. Often in the literature it has been implied, if not specifically noted, that the success of a particular investigation is a direct consequence of the care and techniques used in the fabrication stage of suitable structures and indeed that the mortality rate among completed structures is high due to testing.

It is the purpose of this endeavor to demonstrate that Schottky emission devices can be fabricated from commercially obtainable materials and with techniques and equipment of ordinary laboratory variety. The results obtained following this approach are fairly well reproducible and a simple, non-destructive testing method is presented. Of interest, is the apparent disappearance of the Schottky phenomena for insulating films of thicknesses greater than about one-hundred and fifty angstroms for the structures tested.

CHOICE OF MATERIALS

Thin films of aluminum oxide (Al₂O₃) sandwiched between aluminum and gold metal films were prepared by vacuum deposition of aluminum on precleaned glass
slides, oxidizing the surface by anodic treatment, and then depositing a gold film over the oxide. See Figure 1.

Figure 1 - Cross-section of thin-film structure.

Glass microscope slides were chosen as a substrate primarily because of the smooth non-orientated surface available upon which a thin film of metal could be evaporated, the surface of which would take on the same characteristics as the substrate, thereby producing a metal surface of maximum flatness and smoothness.

This requirement is a necessity if points of high field intensity due to irregular metal surfaces are to be avoided and the calculation of the field intensities over a small area are to be meaningful. Additional advantages of glass lie in the relative inertness of the material with respect to any chemical processes that might be required.
Aluminum was chosen as a base metal as it is easily oxidized by any one of several methods -- on exposure to atmosphere, thermally, or anodically -- and since the resulting oxide is known to exhibit qualities of a good insulator and be free of pores and grain structure if prepared properly. Anodic oxidation of the aluminum base metal was used as the equipment required is a minimum and films of predetermined thicknesses can be produced rapidly.

Preliminary structures were made with both aluminum and gold as the top film of the sandwich. The most reproducible results were obtained with gold. The reasons behind this are not fully understood; however, it appears that the deposition of the gold film over the aluminum oxide causes less damage to the oxide than the deposition of aluminum under similar conditions. This is supported by the observation that almost fifty per cent of the structures made with an aluminum top layer exhibited short circuits upon initial testing. The remaining structures shorted easily at the first signs of current transfer between the metal films. Less than ten per cent of the structures with the gold top film exhibited initial short circuits and of the remaining good structures only ten per cent shorted during
subsequent testing and transfer of current between metal films. All of the structures reported on herein are of the aluminum-aluminum oxide-gold construction.

CLEANING PROCEDURE

The substrate must be scrupulously clean prior to deposition of the aluminum film to be anodized if maximally flat metal surfaces are to be obtained and if problems with film peeling in the anodizing bath are to be avoided. The method used to clean the glass slides is as follows:

(1) Fifteen minute rolling boil in a strong detergent such as alkanox or naccanol
(2) Overflow rinse in tap water for fifteen minutes
(3) Alcohol rinse
(4) Fifteen minute boil in three per cent hydrogen peroxide solution
(5) Rinse in distilled water
(6) Fifteen minute rolling boil in distilled water
(7) Two rinses in distilled water
(8) Store under distilled water until used.
FORMATION OF BOTTOM ALUMINUM FILM

The aluminum base layer was deposited by vacuum evaporation from a tungsten filament at pressures in the $10^{-4}$ to $10^{-5}$ mm Hg. range. The vacuum evaporation plant used was a prototype designed for application of gold to electron microscope specimens. This evaporation plant featured a kinetic pumping system utilizing an organic oil in the diffusion pump. An important feature of this system is the absence of a cold trap or other trap between the diffusion pump and the bell jar and the subsequent absence of any reduction of diffusion pump vapors backstreaming into the bell jar.

Apparently this rather violent departure from previous procedures, where considerable attention was given to keeping the vacuum as "clean" as possible, produced little effect on the final operation of the specimens. It should be emphasized at this point, however, that good vacuum practice was followed throughout and all fixtures and materials that went inside the bell jar were cleaned by steps (1) through (3) as outlined on page 5 and that consideration was given to the general cleanliness of the vacuum operation.

Soft aluminum wire from an aluminum conductor of ordinary purity was specifically used for the bottom
film to construct the samples in contrast to the high purity (99.999%) aluminum used by other workers. Upon spectroscopic analysis, this aluminum proved to be of approximately 99.9% purity with copper being the major impurity of concentration between 0.1% and 0.01%.

(Detailed analysis in appendix A) Approximately fifty milligrams of aluminum were evaporated at a distance of eight to ten centimeters from the substrate to form the bottom film. According to Bond (1, p. 431, fig. 5) the film thickness would be two to three-thousand angstroms thick. This is adequate to provide for the formation of aluminum oxide layers of thicknesses up to two-hundred angstroms as desired here.¹

Aluminum films were evaporated through an aluminum mask simultaneously onto three one inch by three inch glass slides to produce stripes longitudinally orientated as shown in Figure 2 on page 8.

On the right hard edge is depicted a stripe of silver paint which served to connect all the aluminum stripes together during the anodizing process.

¹The formation of Al₂O₃ on an aluminum surface produces an oxide thickness of from 1.38 to 1.6 the thickness of the aluminum from which it was formed. See reference 2, p. 348.
ANODIZING PROCEDURE AND APPARATUS

Within one or two hours of the preparation of fresh aluminum base films, these films were anodized to produce the desired thickness of aluminum oxide. This procedure was followed since aluminum readily oxidizes in air at room temperature. Oxide thicknesses of fifteen to twenty angstroms grow fairly rapidly, but a further growth proceeds slowly reaching a limiting thickness of forty-five angstroms in a matter of a month or so (2, p. 344).

The anodizing solution used was a three per cent solution of tartaric acid in distilled water with the addition of a small amount of ammonium hydroxide solution to adjust the pH to approximately 5.5 (2, p. 347). It is essential that the oxide formed be non-solvent in the electrolyte used for anodizing if non-porous oxide
films are to be obtained. The tartaric acid solution satisfies this requirement. The slides were clipped at the end with the silver paint connecting the stripes to make electrical connection and hung in a glass beaker filled with the anodizing solution. The cathode was merely a piece of aluminum foil hung opposite the slide. The power supply and metering is shown below in Figure 3.

![Diagram of Apparatus for anodic oxidation of aluminum films.]

Holland (2, p. 347) reports that the formation of aluminum oxide is substantially complete after about two minutes in the anodizing cell and that the oxide thickness is related linearly to the voltage across the cell for voltages up to two-hundred volts. The
oxide forms to a thickness of thirteen angstroms per volt applied to the anodizing cell and the quality of the oxide film at any time during the process can be surmised from the reading of the ammeter in series with the anodizing cell. For the geometry and range of voltages used here the oxide formation was considered essentially complete when the anodizing current dropped below fifty microamperes. This required approximately four minutes for all oxides produced. Figure 4 shows the cell current as a function of time for a typical anodizing run.

Figure 4 - Variation of anodizing current with time for constant cell voltage of five volts.

The figure above indicates that as the oxide layer forms it effectively insulates the aluminum from the
anodizing solution and thereby increases the cell resistance slowing the rate of oxide formation. Notice also that the curve indicates relatively high currents if extrapolated back to zero time. Experience has shown that this high current will cause the aluminum films to fuze where they enter the anodizing solution unless limiting resistance is inserted in series with the anodizing cell. This is the function of the variable resistance shown in Figure 3.

The filter is used since the film thickness depends upon the peak voltage applied to the cell. This allows a more accurate measurement of the pertinent voltage and better control of oxide thicknesses. A procedure that proved to be the most efficient for producing oxides of predetermined thicknesses is as follows:

(1) With the cell disconnected from the power supply set the open circuit voltage to the desired value. For example, if five volts is set as the open circuit voltage, the final film thickness will be approximately five times thirteen or sixty-five angstroms.

(2) Open switch $S_1$ and allow the capacitors to discharge through the voltmeter. A one-thousand
ohm per volt instrument was used here.

(3) Load the cell with the sample to be anodized and connect to the power supply.

(4) Upon closing the switch $S_1$ the cell voltage will rise at a finite rate ending at the open circuit voltage due to the time constant of the cell and circuit resistances and capacitances.

This procedure eliminated problems of fuzed films associated with the current surge due to the initial low value of cell resistance.

FORMATION OF THE TOP GOLD FILM

The gold top film was deposited from a tungsten filament by vacuum deposition in a manner similar to that used to form the aluminum bottom films. Approximately seventy-five milligrams of gold was evaporated at a distance of eight to ten centimeters to form the top film of the sandwich. A film thickness of between two hundred and four hundred angstroms was thus obtained.

The mask that was used to produce the aluminum bottom stripes was again used to produce the top gold stripes. For this evaporation the mask was rotated ninety degrees with respect to the three glass slides to produce a cross hatching of anodized aluminum and gold as depicted
below in Figure 5.

Figure 5 - Glass slide with array of completed thin-film structures. The left hand portion of the slide shows how the individual structures were separated to allow for individual testing. (Approximately to scale)

At every point where a gold stripe lay over an anodized aluminum stripe a completed thin-film structure is obtained. In this way a multiplicity of structures are fabricated for each slide processed. The gold stripes were severed at points between the aluminum stripes as indicated in the left portion of Figure 5 so that each structure could be tested separately. This was done by erasing the gold from the glass slide at the appropriate points with an ordinary pencil eraser that had been sharpened to a point.
The electrical characteristics of the thin-film structures are of major interest. In particular, the current transferred between the metal films through the insulating oxide film as a function of voltage applied between the metal films has been recorded for a variety of oxide thicknesses. This volt-ampere characteristic may be obtained in a number of ways, both dynamic and static. A static method of testing was used here primarily because of its simplicity, but also because of the non-destructive features that could be built into the test circuit. The unsuspected additional dividend of being able to observe slow drift changes in the volt-ampere characteristics also appeared during the collection of data. Figure 6 shows the test circuit.

![Test Circuit Diagram](image-url)

Figure 6 - Static test circuit for thin-film structures

The difference in the readings of $V_1$ and $V_2$ gives the current, in microamperes, transferred between the metal films while $V_2$ gives the voltage between the metal films directly. In the test set up used to obtain the volt-
ampere characteristics of the structures tested, a Hewlit Packard model 412A chopper stabilized vacuum-tube-voltmeter with two-hundred megohms input impedance was used at $V_2$. This precluded the necessity of making meter corrections to the current in the ranges of interest here.

Electrical connections for test purposes may be made by clipping onto the silver paint stripe (see Figure 5) which connects all of the aluminum stripes to one side of the test circuit and by probing the gold film next to the thin-film structure under examination with a fine wire. This precludes the possibility of incurring mechanical damage to the thin-film structure. Volt-ampere characteristics were obtained for each of the two possible polarities for each thin-film structure tested, i.e., with the aluminum film negative, gold film positive, and with the aluminum film positive, gold film negative.

TEST RESULTS

Typical volt-ampere curves for a thin-film structure are shown in Figure 7. Curves for both polarities of the aluminum film are shown for comparison. The relative position of the curve for the aluminum positive
occurred at a higher voltage than the curve for the aluminum negative for all but two of the thirteen different slides tested.

![Diagram](image)

**Figure 7 - Volt-ampere characteristics of thin-film structure.**

If the voltage at which a transfer current of three microamperes is plotted as a function of the anodizing voltage for all of the thirteen slides tested the relationships shown in Figure 8 result. Since the film thickness is assumed linearly related to the anodizing voltage Figure 8 shows that the field strength required to achieve a three microampere transfer current decreased slightly for the thicker films. It is interesting to note here that for Al$_2$O$_3$ films thicker than shown in Figure 8 (i.e. thicker than about 150 angstroms), it was not possible to obtain characteristic curves as shown in Figure 7. At the first signs of transfer
Figure 8 - Applied voltage to achieve 3 microamperes transfer current as a function of anodizing voltage and \( \text{Al}_2\text{O}_3 \) film thickness.

current these thicker films apparently broke down and produced permanent short circuits. The films produced with twelve volts of anodizing voltage also exhibited a definite tendency to break down when tested with the aluminum film negative which placed the greatest voltage across the aluminum oxide. At lower values of applied voltages the films appeared stable against this type of failure.

As transfer currents were increased for a particular film, a noticeable drift in the voltage across the structure was observed. The drift was in such a direction as to lower the voltage applied when the anodized
film was negative and to raise the applied voltage when the anodized film was positive. The drift increased as current increased and also as structures that required higher voltages for the same transfer current were tested. The effect on the curves is shown in Figure 8 by arrows indicating the direction of drift. In general the structures stabilized in their characteristic in a matter of a minute or two each time the transfer current was increased. Points were recorded after this time elapse.

Structures were easily destroyed by allowing sufficient transfer current to pass through the oxide film. Some structures failed with as little as ten microamperes while others required as much as five-hundred microamperes to produce failure. The magnitude of the current required to produce failure seemed to have no correlation with the physical area of the structure. With careful adjustment of the current, slow failures could be produced requiring a minute or more for complete destruction of the current transfer properties of the structure. Observation of a number of these failures under a microscope indicated that points in the structure would fail apparently one at a time with the active point shifting as the previous point failed
until the entire structure was consumed and became an 
open circuit. Visual evidence of this in early 
structures with an aluminum bottom and top film was the 
gradual disappearance of the metallic appearance of the 
structure until the entire structure became transparent 
to the naked eye. In the later structures with the 
gold top film the disappearance of either film did not 
occur; however, the failure was accompanied by the 
appearance of small boils on the surface of the gold 
film. The size of the boils was about the same as the 
size of the transparent spots on the previous structures, 
each of slightly different size, but in general being 
about the size of a pin point. Again the failure 
seemed to progress until the entire surface of the 
structure was covered with the boil like deformity and 
an open circuit resulted. These observations are taken 
to indicate that the current transfer phenomena observed 
occurred only at tiny points on each structure tested 
and that any measurements or computations involving the 
geometric area of the structure would be meaningless.

DISCUSSION

The problem that asserts itself at this point is to 
determine the nature of the current transfer mechanism 
represented by the test results and if possible to
identify it with one of the presently popular theories or models. Electrons may escape from a metal by either or a combination of two mechanisms, these being by thermionic emission or by field emission. If the thermionic emission is aided by the application of an appropriate electric field the thermionic current is enhanced and this is known as the Schottky effect. Simple, but appropriate, models illustrating these ideas are conveniently developed with the aid of the energy level or band theory of electronic activity in solids.

An electron existing within the bulk of a solid material resides at a lower potential energy than a similar electron far removed from the metal. Thus the electron is within an energy barrier represented by the metal surface or in terms of quantum theory the electron is in a potential well. To escape the confining influence of the solid metal and become "free" the electron must obtain by some manner enough energy to lift it over the potential barrier. The situation that presents itself to an electron existing in the conduction band of a typical metallic conductor is depicted in Figure 9 on page 21. The cross hatched section shown represents the conduction band for electrons in the metal. The Fermi energy, $E_f$, represents the energy at which the
Figure 9 - Energy diagram for an electron at the surface of a metal.

The probability is one-half that an electron will exist in an energy increment $E_f + \Delta E$. At normal temperatures the distribution of electrons in the metal is as shown in Figure 10 below.

Figure 10 - Distribution of electrons with respect to energy in a metal.
This distribution is derived in most textbooks dealing with modern physics -- for example see Ref. 6, p. 259. The dotted portion of the distribution indicates the situation at a temperature of absolute zero. Here the probability of electrons existing within an increment of energy changes very rapidly at the Fermi energy, being zero at an energy slightly larger than the Fermi energy. An increase in temperature modifies this distribution as shown by the solid portion of the distribution function. The increase in temperature can be thought of as causing electrons from the area indicated by "A" in Figure 10 to spill out and occupy positions in area "B." The curve retains its symmetry about the Fermi energy which is the point at which $N(E)dE$ is equal to one-half. At room temperature (300 K) for example the energy, $E_{\frac{1}{2}}$, at which $N(E)dE$ is $1/e$ (0.37) times the value of the Fermi energy occurs at an energy of only about one-fortieth of an electron volt above the Fermi energy while the Fermi energy for most metals lies between five and ten electron volts above the bottom of the conduction band. Thus it is seen that it is a good approximation to assume that the majority of electrons of interest lie at the Fermi energy. With this in mind it follows that the energy required to free
an electron from the metal ($q\phi$ in Figure 9) will be the difference between the Fermi energy and the energy a great distance away from the metal surface. This is the so-called "work function" of the material. For most metals the work function is in the neighborhood of four electron volts.

A suitable energy model for the thin-film structures investigated here is shown in Figure 11. The metals, $M_1$ and $M_2$ are separated by an insulating region, $I$, of narrow width.

![Figure 11 - Energy model for thin-film structures.](image)

- (a) structure in equilibrium with no external potential applied.
- (b) small external potential applied, $M_2$ positive.
- (c) large field intensity existing in insulator, $I$. 
The metals have been shown to have equal work functions. This will be approximately true for aluminum and gold and most other metals. If $M_1$ and $M_2$ are identical metals the equivalence of the work functions is apparent to the degree that the surface conditions are equivalent.

Figure 11 may be applied to either thermionic emission or to high-field emission. For thermionic emission the electrons must acquire energy at least equal to $q\phi$ above the Fermi level in order to traverse from one metal to the other over the barrier represented by the intervening insulator. If one metal is made positive with respect to the other as shown in Figure 11-b the barrier height is increased by the amount $V$ for electrons attempting to travel from $M_2$ to $M_1$. The barrier height for electrons traveling from $M_1$ to $M_2$ remains the same however. The net result is that fewer electrons pass from $M_2$ to $M_1$ than pass from $M_1$ to $M_2$ and a net electron current from $M_1$ to $M_2$ can be detected.

For high-field emission consider Figure 11-c where the field intensity in the insulating region is high. Here the effective width of the barrier is made smaller by the applied field and it is possible by quantum mechanical tunneling for electrons with energies
less than the barrier height, $q\phi$, to appear on the opposite side of the barrier. This effect is temperature independent since the largest population of electrons occurs at the Fermi energy, therefore the tunnel current is composed, for the most part, of electrons with an energy equal to the Fermi energy. The tunnel current is, however, strongly dependent on the magnitude of the electric field since the width of the barrier is determined by the electric field.

It is apparent that if the current transfer observed for the thin-film structures reported here is independent of temperature this would provide evidence of the existence of the tunnel phenomena or high-field emission. Upon performing a qualitative test for temperature dependence on several of the structures, it was found that the observed transfer current was strongly dependent upon the temperature. In general the structures failed before reaching a temperature of seventy-five degrees Centigrade which precluded obtaining quantitative temperature characteristics.

The thermionic emission equation which includes the effect of an applied electric field on the emission (Schottky effect) is:

$$j = A_0 T^2 \exp \left\{ -\frac{q}{kT} \left[ \phi - \left( \frac{qE}{4\pi \epsilon_0} \right) \right] \right\}$$

(Ref. 6, p. 371)
where:  
\( j \) is the emitted current density 
\( A_0 \) is the Richardson-Dushman constant,  
\( \frac{1.20 \times 10^6}{\text{amp/m}^2\text{deg}^2} \)  
\( T \) is the absolute temperature  
\( q \) is the electronic charge  
\( k \) is Boltzman's constant  
\( \phi \) is the work function of the emitter  
\( E \) is the field intensity existing between the emitter and collector electrodes  
\( \epsilon_0 \) is the permittivity of free space.

At a constant temperature, \( T \), a plot of the natural logarithm of the emitted current density as a function of the square root of the applied field intensity should produce a straight line. Since the active area of the structures tested is unknown a plot of the natural logarithm of the observed transfer current vs. the square root of the applied voltage should produce a straight line if Schottky emission is being observed. This is assuming that the active area of the structure does not change during testing. Plotting the characteristic from Figure 7 for the case with the aluminum negative results in Figure 12 on page 27. The characteristic depicted in Figure 12 is typical for the structures tested. This is taken as strong evidence that the
At the outset one of the goals of this investigation was to demonstrate a current transfer process through an insulating layer which has been referred to extensively in the literature as "electron tunneling." Upon analysis it has been shown that the observed current transfer process fits the theory applicable to Schottky emission well. Indeed, it has also been shown in recent literature (7) that reports previously attributable to electron tunneling also fit the Schottky theory well. The question is raised as to the real difference between the phenomena termed electron tunneling and Schottky emission. It is possible that the present concept of electron tunneling through a barrier is not required to explain the observed phenomena, but
rather that the barrier is actually lowered by a non-uniform electric field distribution in the insulating film. This would preclude the necessity of the electron tunneling concept and make the Schottky emission concept seem plausible. The reconciliation of this apparent difference in the explanation of the observed phenomena is not in sight. It is entirely possible that a theory may be found that will enhance both points of view. The preliminary work accomplished here, however, favors the Schottky emission concept.

In view of the similarity of the results obtained here and those obtained by others (7) it is apparent that the reduced purity of the materials used to construct the thin-film structures do not inhibit the current transfer mechanism. In fact, future investigations may show that the impurities present in the aluminum-oxide enhance the phenomena rather than deter it. If the impurity concentrations in the oxide are thought of in terms of doping levels for semiconductors the difference between 99.9% purity and 99.999% purity is not really great. Along with this the vacuum techniques used to produce the metallic films are apparently adequate for the purpose. It is felt that the goal to demonstrate the current transfer processes through thin insulating films using modest techniques
and equipment has been achieved.

A characteristic common to most insulating films is the decrease in electric field strength at which film breakdown occurs as the film thickness is increased. As the thickness of the oxide layers was increased the breakdown field strength was lowered until at a film thickness of about one-hundred-fifty angstroms the field strength required to maintain Schottky emission was about the same as that required to cause breakdown of the film. Above this film thickness the film would preferentially puncture before a field intensity high enough to cause Schottky emission could be attained.

The observation of the drift properties of the volt-ampere characteristic of the structures leads to some interesting conjectures. At the interface between the aluminum base film and the oxide layer the transition from aluminum to oxide may not be abrupt. Rather it is likely that it occurs relatively gradually and that the existence of aluminum atoms in the oxide in this transition region may act in a manner similar to the doping impurities in a semiconductor. The transition at the oxide-gold interface is more abrupt however, due to the different method of construction. This proposed region with semiconductor-like properties
is convenient to explain the drift observed in the volt-ampere characteristics as follows.

The impurities create additional sources and traps for electrons at the edge of the oxide layer. The situation might be as shown in Figure 13.

![Illustration of impurity levels in aluminum oxide film.](image)

Figure 13 - Illustration of impurity levels in aluminum oxide film.

The impurity levels are shown at one position in Figure 13 for simplicity. In the actual situation the impurities are distributed over a small distance close to the aluminum film. As indicated, the bottom film is considered positive with respect to the top film.

For the situation where the aluminum film is positive (Figure 13-a) electrons leaving the gold film may elect to terminate their travel through the oxide on one of the impurity traps available close to the aluminum film. The result is that these traps fill up giving rise to a space charge layer in the oxide film.
This space charge reduces the field intensity in the oxide, and likewise reduces the transfer current or requires a higher applied voltage for the same value of transfer current. For the other situation when the gold film is positive (Figure 13-b) the filling of the impurity traps causes a space charge layer that increases the field intensity in the oxide and the transfer current increases or the applied voltage required to maintain a given value of transfer current decreases. The time required to fill the traps and establish the space charge layer is a matter of seconds and the effects are readily observed as the film and applied voltage come into equilibrium.

CONCLUSIONS

1. The current transfer phenomena can be demonstrated with materials of common commercial purity and with modest equipment and techniques.
2. A simple energy model based on the concepts of thermionic emission satisfactorily describes the situation as seen by an electron in a metal.
3. The transfer current is highly temperature dependent for the structures tested.
4. The characteristic transfer current observed fits
Schottky plots very well, leading to the conclusion that the observed phenomena is due to field enhanced thermionic emission. This is somewhat at variance with reports in the literature.

5. The drift properties of the volt-ampere characteristics lead to the proposal of a semiconductor-like region in the oxide film and the existence of electron traps within this region.

6. For oxide thicknesses greater than about one-hundred-fifty angstroms, the Schottky emission is preceded by failure of the oxide film.

RECOMMENDATIONS

1. Of most interest are the thermal characteristics of the volt-ampere curves for the thin-film structures. These characteristics could be investigated in the temperature range extending from liquid nitrogen temperature to room temperature with fairly simple apparatus. Further support of the theory that the transfer current is a thermionic current could be obtained by comparing the data so obtained with the thermionic emission equation. This data could also be used to determine if a small tunnel current actually existed along with the thermionic current.
2. The operation of devices based on the observed phenomena would be the next natural step. It would be most interesting to determine if operational devices such as described in the literature could be built using the same constructional techniques as outlined here. These devices are termed "Majority Carrier Amplifiers" and are described in references 3, 4 and 5.
BIBLIOGRAPHY


APPENDIX
APPENDIX

Qualitative spectrographic analysis of aluminum used for bottom films of structures constructed to demonstrate current transfer by Schottky emission.

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<th>Concentrations</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>over 10%</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1% to 0.01%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.01% to 0.001%</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.01% to 0.001%</td>
</tr>
<tr>
<td>Iron</td>
<td>below 0.001%</td>
</tr>
<tr>
<td>Silver</td>
<td>below 0.001%</td>
</tr>
</tbody>
</table>

This analysis was performed by the State of Oregon Department of Geology and Mineral Industries, Portland, Oregon on OSU order No. E 126434.