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Electron Barriers in Al-Al_2O_3-SnTe and Al-Al_2O_3-GeTe Tunnel Junctions*

The tunneling characteristics of junctions consisting of two normal metals separated by a thin insulating film have been analyzed theoretically,[1,2] and the main features of the analyses have been corroborated by extensive experimental studies. On the other hand, relatively little attention has been given to junctions in which one of the metals is replaced by a semiconductor.[3] Recently, we showed that, under certain conditions, such junctions exhibit a negative resistance, as in the Al-Al_2O_3-SnTe system.[4,5] We have continued that investigation and now have derived the electron barrier heights of that system, and have extended our studies to the system in which GeTe replaces SnTe.

The tunneling units used in the work were fabricated by successive evaporations, as reported previously.[4] Since we were primarily interested in characteristics obtaining at relatively high voltages, the units employed a thicker insulator than had been used earlier (these were made by oxidizing Al at elevated temperatures—about 600°K). The semiconducting films of SnTe and GeTe were heavily degenerate *p*-type, having carrier concentrations of 8×10^{20} and 2×10^{20} cm^{-3}, respectively. The current-voltage characteristics, taken mainly at 4.2°K, will be presented only for SnTe junctions in the following, those for GeTe being qualitatively similar.

Figure 1 shows the I–V curves for a typical Al-Al_2O_3-SnTe junction for both polarities of applied voltage and gives its zero-bias energy diagram. It is seen the curve with SnTe positive exhibits negative resistance in the voltage range from 0.6 to 0.9 V. The former value corresponds to the Fermi level, F_p, of SnTe and the difference, 0.3 eV, gives its energy gap, E_g, as reported earlier.[4] The behavior of this curve at higher voltages and that of the other curve with Al positive are seen to be similar in shape to the behavior of a metal-metal tunnel junction.[1,2] That is, the current follows approximately an exponential function of bias in the intermediate voltage range, increases somewhat sharply at a bias corresponding to the barrier height, and levels off thereafter, where the tunneling is known to be in the Fowler-Nordheim region.

Theoretically, the tunneling current can be calculated using the double integral over energy and transverse momentum.[6] By using appropriate approximations, analytical expressions for the current have been derived over the whole voltage range. The experimental results are found to be in good agreement with these expressions;[7] hence, the barriers and other parameters can be deduced. For example, analyses applied to the data of Fig. 1 give 3.1 and 1.9 eV for barriers ϕ_1 and ϕ_2 (SnTe-Al_2O_3 and Al-Al_2O_3, respectively), with a built-in asymmetry of $\phi_0 = \phi_1 - \phi_2 = 1.2$ eV as shown in Fig. 1. These values are subject to minor corrections due to effects of image force and band bending which have been neglected; also, we have used a single tunneling electron mass in our formulation.

For our present purpose, the expression for the current can be simplified to the form below, which is a good approximation at relatively high voltages ($V_{\mathrm{Al}^+} > 1\ V$ and $V_{\mathrm{SnTe}^+} > 2\ V$).[7] After simplification, we have

$$I = \frac{Aq\phi}{4\pi^2\hbar s^2}\left(1 + \frac{cs^2T^2}{\phi}\right)\exp\left[-\frac{2(2m\phi)^{1/2}s}{\hbar}\right],$$

where A is the tunneling area and c is a constant so small that the term involving temperature is much smaller than unity.[7,8] The average tunneling barrier ϕ and the effective

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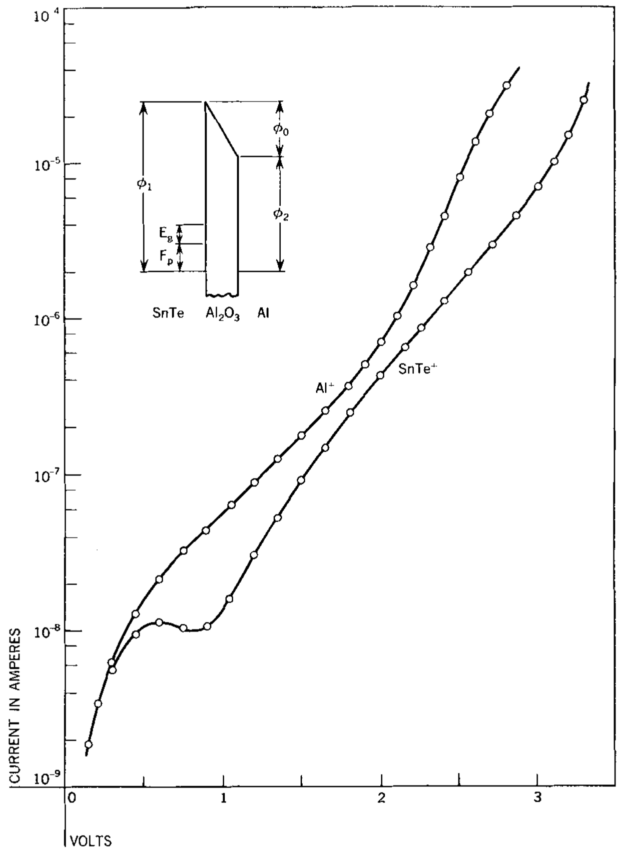

Figure 1. Current-voltage characteristics of Al-Al_2O_3-$SnTe$ junction at 4.2°K.

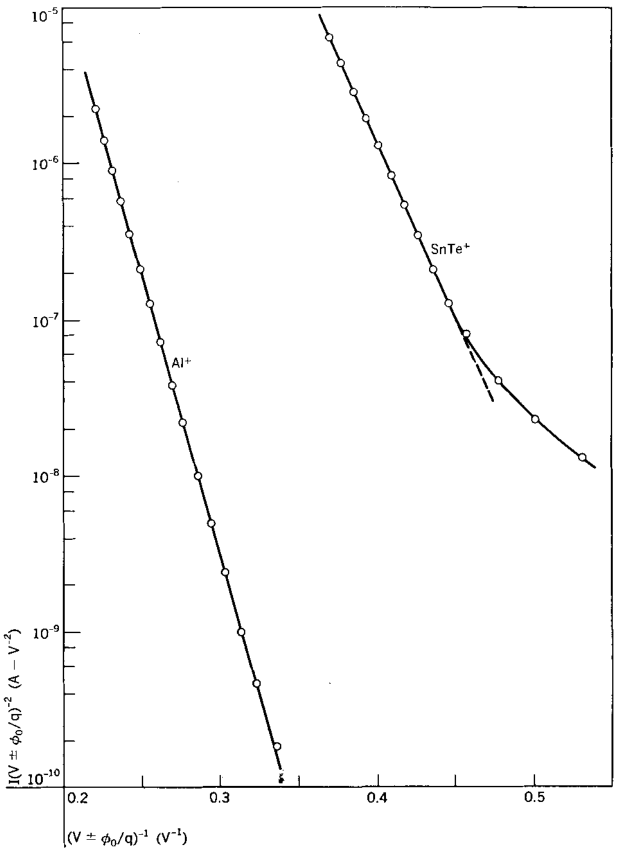

Figure 2. Fowler-Nordheim plot of Al-Al_2O_3-$SnTe$ junction at 4.2°K.

tunneling distance s are defined as follows: For Al positive with $qV < \phi_2$, we have $\phi = (\phi_1 + \phi_2 - qV)/2$, and $s = d$, the insulator thickness; and with $qV > \phi_2$, we have $\phi = \phi_1/2$, and $s = \phi_1 d/(qV + \phi_0)$. For the other polarity, SnTe positive, ϕ_1 and ϕ_2 are interchanged. It is seen that the equation is identical to that which governs the process of metal-to-metal tunneling.[8] This identity explains the similarity existing between the I-V curves of our junction and those of a metal-metal junction, which we mentioned above. As a result, methods used to determine the barriers in a metal-metal system can be applied, in the appropriate voltage range, to the present case.

The isothermal current-voltage characteristics in the Fowler-Nordheim region are considered first. Substituting expressions for ϕ and s into the equation gives, except for constant factors,[2] the same equation as that for field emission,[9] in which $\ln I(V \pm \phi_0/q)^{-2}$ varies linearly with $(V \pm \phi_0/q)^{-1}$. To investigate experimentally the current in this region, units with a very thick oxide were used. The results for one such unit are plotted in Fig. 2 where $\phi_0 = 1.2$ eV has been used. It is seen that the theoretically predicted behavior is followed over several decades of the current level. The absolute values of ϕ_1 and ϕ_2 can not be determined without knowing m and d. However, ϕ_1/ϕ_2 can be found from the ratio of the slopes or the ratio of the zero-intercepts of the two straight lines. These values are 1.51 and 1.66, respectively, giving $\phi_1 = 2.9$ eV or $\phi_1 = 3.2$ eV, again respectively, if ϕ_2 is chosen to be 1.9 eV. We may proceed, as in a metal-metal junction, to obtain an estimate of the insulator thickness and the effective tunneling area. Using m equal to half the free electron mass, d is found to be about 40 Å and A to be about 10% of the geometrical area. These results obtained from the two polarities agree within 10% and are considered reasonable.

We next recall that there is a temperature dependent factor in the equation. This term, which may be neglected for analyses of isothermal characteristics, provides an independent means of finding the barrier heights.[8,10] If $(I_T - I_0)/I_0$, the fractional change of current between zero temperature and T, is plotted versus V, distinct peaks should occur at voltages corresponding to the barriers,

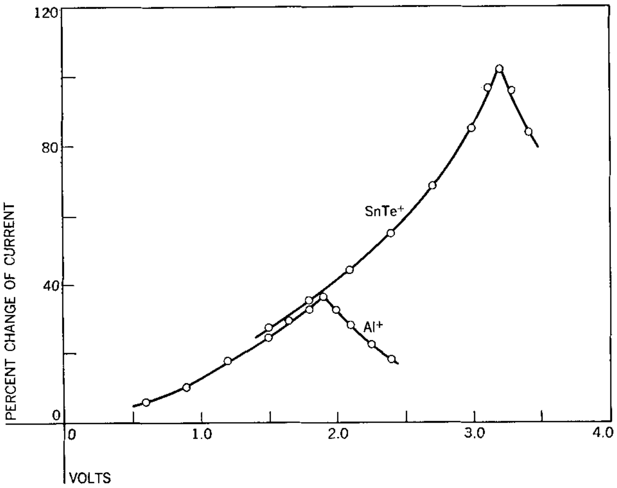

Figure 3. Percent change of current between 4.2°K and 100°K as a function of voltage for Al-Al_2O_3-SnTe junction.

as can be shown readily by substituting the definitions of ϕ and s into the equation. Figure 3 shows the results plotted in this fashion. The temperatures at which these measurements were made are 4.2°K and about 100°K. The peaks are seen to show up as predicted at 1.9 and 3.2 V corresponding, respectively, to ϕ_2 and ϕ_1. It should be mentioned that the percentage change, as in the metal-metal junction,[10] is larger than that predicted theoretically. This discrepancy may be partly explained by the temperature dependence of the energy gap,[5] resulting in lower barriers at higher temperatures.

In summary, we find for the SnTe system $\phi_1 = 3.1$ eV and $\phi_2 = 1.9$ eV with an uncertainty of 0.2 eV. For the Al-Al_2O_3-GeTe system, the junction behavior is similar to that of SnTe. The GeTe film has a Fermi level of 0.4 eV and an energy gap of 0.2 eV, and the barriers evaluated in the same manner are $\phi_1 = 2.8$ eV and $\phi_2 = 1.9$ eV. With these parameters determined and the work function of Al known, $W_{Al} = 4.2$ eV, the work function and electron affinity of the semiconductors can be found. Thence, $W_{SnTe} = 5.4$ eV, $W_{GeTe} = 5.1$ eV, and the electron affinity is 4.5 eV for both the materials.

References

1. R. Stratton, *J. Phys. Chem. Solids* **23**, 1177 (1962).
2. J. G. Simmons, *J. Appl. Phys.* **34**, 1793 (1963).
3. P. V. Gray, *Phys. Rev.* **140A**, 179 (1965).
4. L. Esaki and P. J. Stiles, *Phys. Rev. Letters* **16**, 1108 (1966).
5. P. J. Stiles, L. Esaki and W. E. Howard, paper presented at 10th Int. Conf. Low Temp. Phys. Moscow, 1966; and L. Esaki, paper presented at Int. Conf. Semiconductor Phys., Kyoto, 1966.
6. W. A. Harrison, *Phys. Rev.* **123**, 85 (1961).
7. L. L. Chang, P. J. Stiles, W. E. Howard, and L. Esaki, to be published.
8. John G. Simmons, *J. Appl. Phys.* **35**, 2655 (1964).
9. W. Franz, in *Handbuch der Physik*, Vol. 17, p. 155, Springer, Berlin (1956).
10. S. R. Pollack and C. E. Morris, *Trans. Metallurgical Soc. of American Inst. of Mining, Metallurgical, and Petroleum Engineers* **233**, 497 (1965).

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