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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF OPTIMUM SUPERCONDUCTING THIN-FILM TUNNELING DEVICES AND THE APPLICATION TO EHF

Final Report

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ABSTRACT

Theoretical I-V characteristics for several superconductor junctions are predicted with the aid of the digital computer and a method is established which allows one to choose an optimum operating temperature. Two junctions, Ta-Ta_2O_5-Nb and Nb-Nb_2O_5-V, were selected for experimental work because each has a predicted optimum operating temperature above that of boiling helium at atmospheric pressure. Experimental verification is expected soon although it has not yet been obtained due to fabrication difficulties. Recommendations for future work are outlined.

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INTRODUCTION

The purpose of the work reported here is to extend the investigation of the possibility of developing a practical amplifying device based on the negative resistance property exhibited by two superconducting metals separated by a thin insulating film. Preliminary studies have indicated that such a device is suitable for operation at rf and microwave frequencies.[1-3] The main advantage of an amplifier of this nature is the inherent low noise operation made possible by operating at temperatures close to absolute zero. For deep space communications and guidance systems low noise operation is of the utmost importance.

Work in this area was begun by the author during the summer of 1967 at the Langley Research Center in Hampton, Virginia under the NASA-ASEE Summer Faculty Fellowship Program. The chief result of the initial investigation was the development of a digital computer program which predicted the I-V characteristics for a given superconducting junction based on the BCS theory. Many combinations of superconducting metals were studied and a few of the most promising were recommended for further study. Also recommended for further consideration were certain refinements in the computer program and a correlation between the physical properties of the junction and the actual current through the junction.

PREDICTION OF THE OPTIMUM TUNNELING JUNCTION

In order to predict the I-V characteristics for a superconducting junction, the following equation given by the BCS theory had to be solved:[4]

$$I = \alpha \int_{-\infty}^{\infty} \rho_1(E)\rho_2(E + eV)\ [F(E)-F(E + eV)]\ dE$$

where e is the electronic charge, V is the applied potential, E is the electron energy, ρ is the ratio of the superconducting to the normal density of states given by

$$\rho(E) = \frac{|E|}{[E^2-\epsilon^2]^{1/2}}$$

and F is the Fermi function given by

$$F(E) = \frac{1}{1+\exp(E/kT)} .$$

In the above equations ϵ is one half of the energy gap, k is Boltzmann's constant, and T is the absolute temperature. The gap energy varies with temperature as shown in Fig. 1. The above equations were evaluated with the aid of the digital computer for different combinations of superconductors. The results were checked against experimentally available data for an $Al\text{-}Al_2O_3\text{-}Pb$ junction [5] and agreed very well. The predicted curves are shown in Fig. 2 and the reported experimental curves in Fig. 3. Other types of metals studied were Al, In, Nb, Pb, Sn, Ta, and V.

Based on the computer studies, two junctions that looked particularly promising were the $Ta\text{-}Ta_2O_5\text{-}Nb$ and the $Nb\text{-}Nb_2O_5\text{-}V$ junctions. The I-V

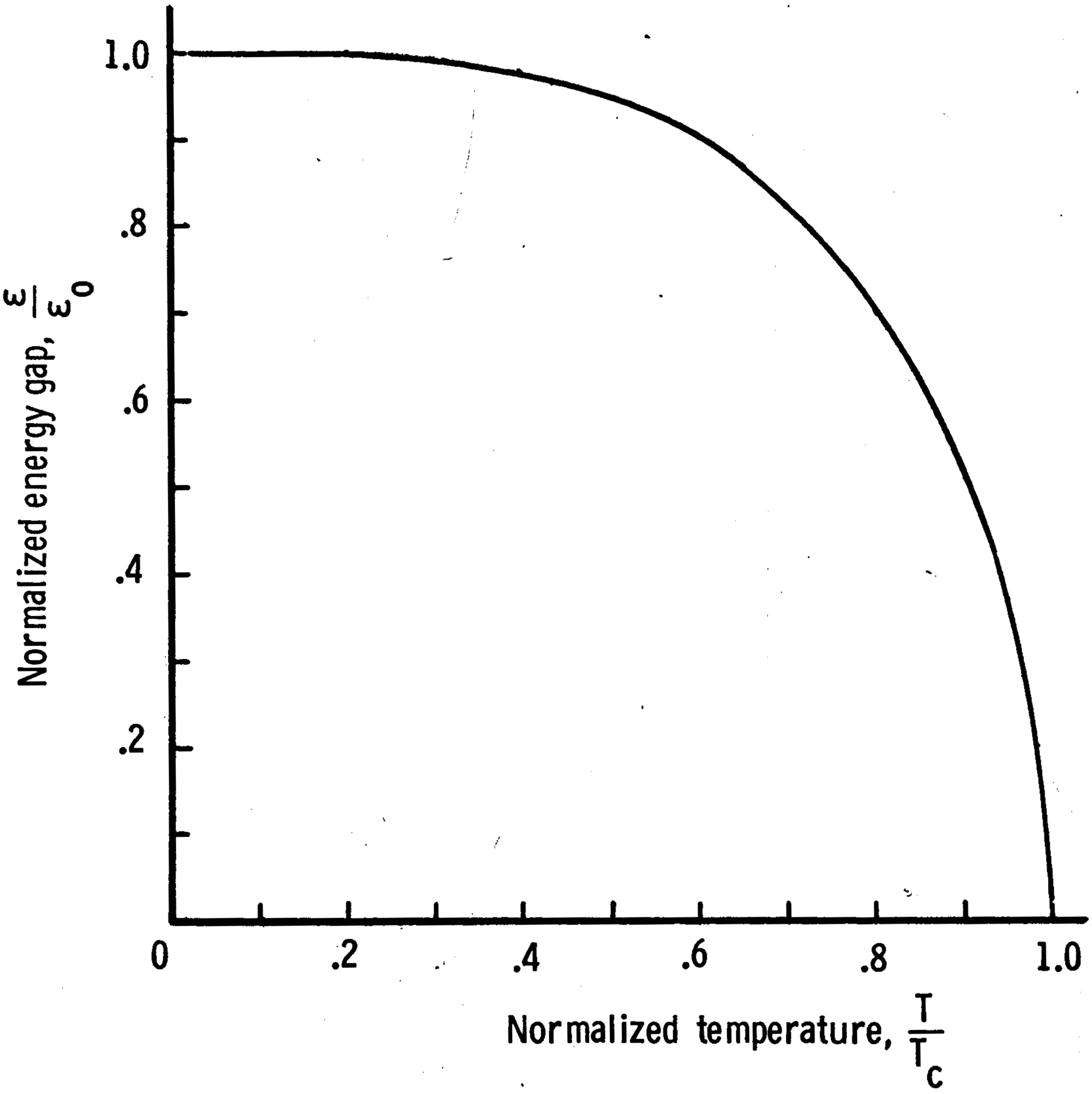


Figure 1.- Energy gap as a function of temperature.

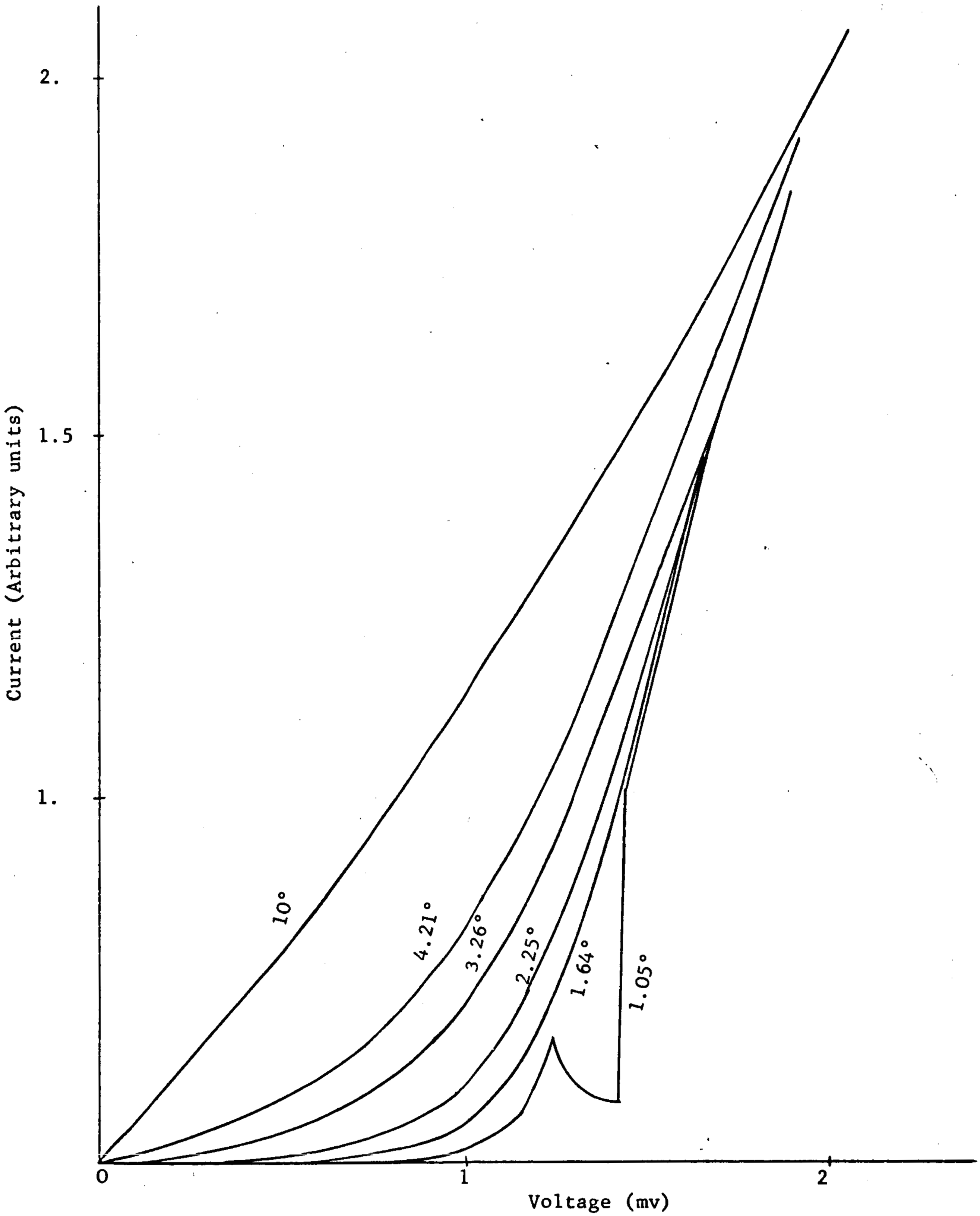
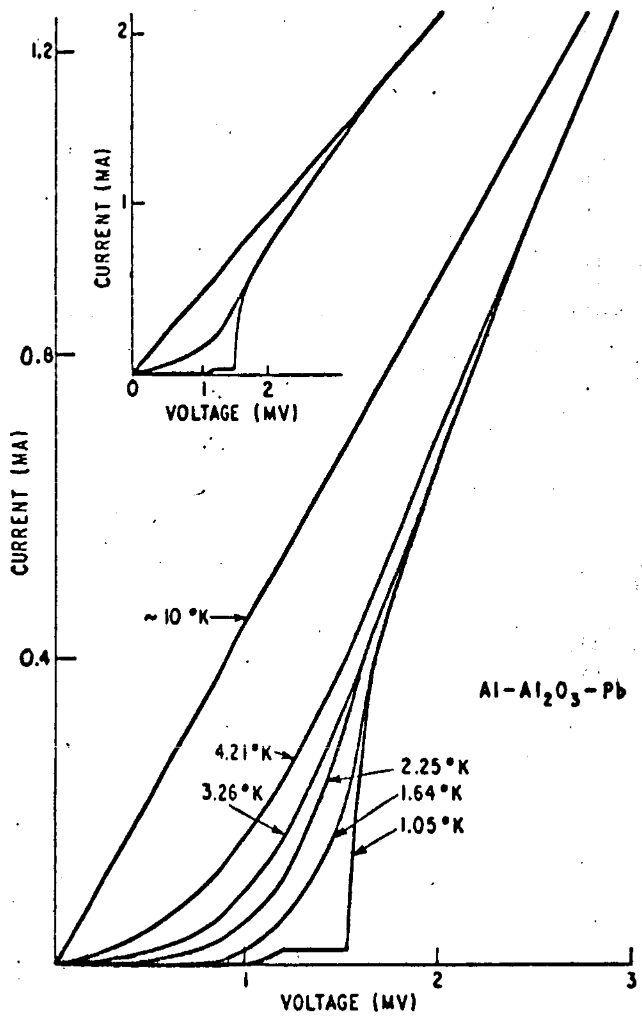


Figure 2. - Theoretical curves for an $Al-Al_2O_3-Pb$ structure. For aluminum T_c= 1.2°K, and for lead T_c= 7.19°K



-Experimentally observed current-voltage characteristics of an Al-Al_2O_3-Pb sandwich for different temperatures. When neither of the metals is superconducting ($T > 7.2°K$) the characteristic is linear, when only Pb is superconductive ($7.2°K > T > 1.2°K$) the characteristic is nonlinear and, when both metals are superconductive ($T < 1.2°K$), a negative resistance range also appears.

Figure 3 - I-V Characteristics for an Al-Al_2O_3-Pb sandwich. (Taken from Fiske and Giaever[6].)

characteristics for the $Ta\text{-}Ta_2O_5\text{-}Nb$ junction are shown in Fig. 4 and those for the $Nb\text{-}Nb_2O_5\text{-}V$ junction in Fig. 5. Since both of these junctions exhibit the negative resistance property above 4.2°K (the boiling point of helium at atmospheric pressure), they would both be ideal for using in a reasonably low cost cryogenic system.

The problem of determining the optimum operating temperature should now be given some consideration. A quantity that plays an important role in this decision is the ratio of the peak current at the onset of the negative resistance region to the valley current at the minimum point in the negative resistance region. The computer was programmed to give these values automatically and a plot of the peak-to-valley current ratio is shown in Fig. 6. As seen from these plots, the peak-to-valley ratio increases with decreasing temperature. The implication here is that one would still be better off operating as close to absolute zero as possible. However, another inspection of Figs. 4 and 5 reveals that at the low temperature, even though the peak-to-valley ratio is large, there is very little practical operating region. In order to obtain a compromise between the large peak-to-valley ratio and small operating current at low temperatures and the small peak-to-valley ratio and large operating current at higher temperatures, the quality factor η is introduced [6]. One arrives at the value for η by multiplying the peak-to-valley ratio by the average current in the negative resistance region, i.e.,

$$\eta = \frac{I_p}{I_v} \cdot \frac{I_p+I_v}{2}$$

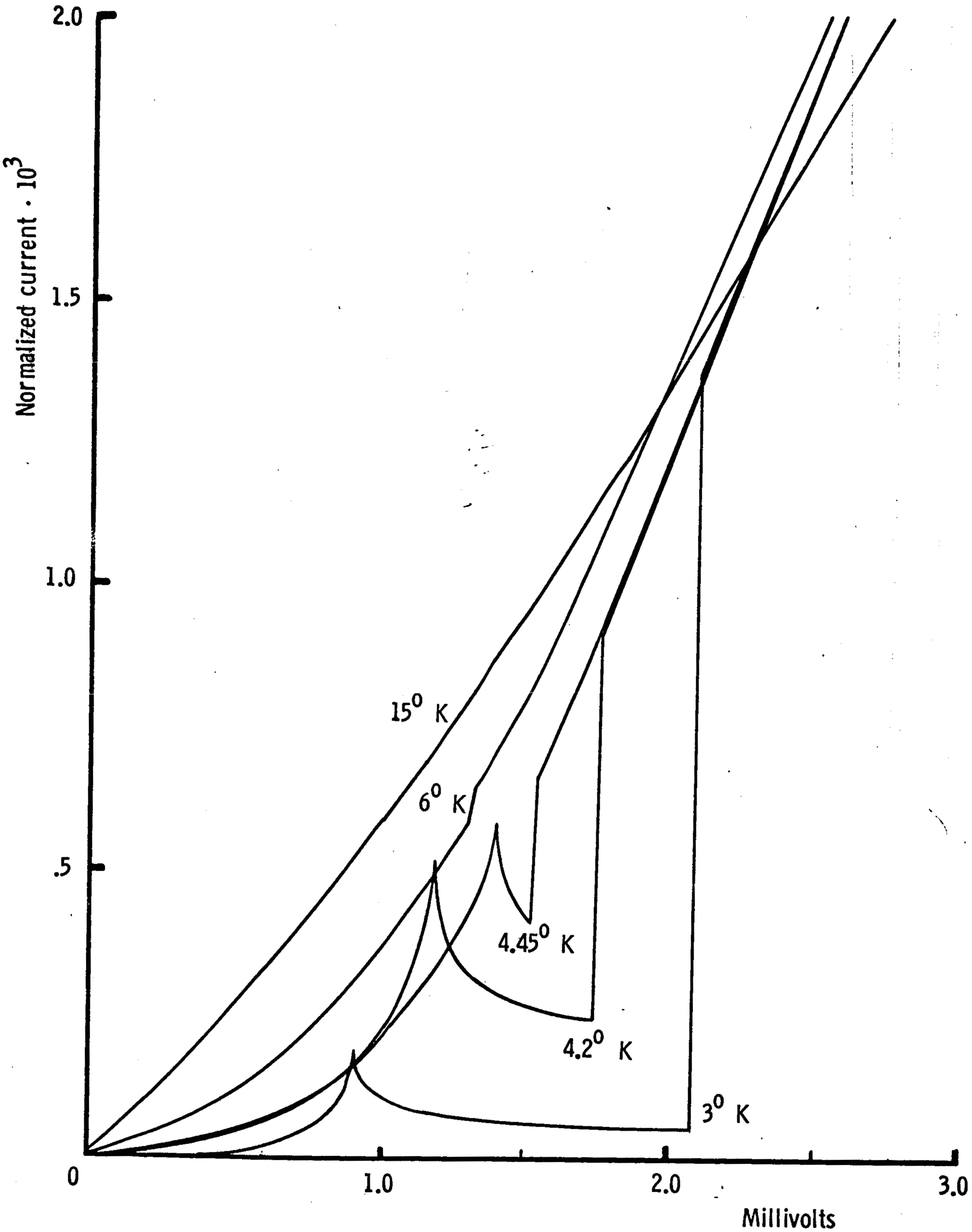


Figure 4.· Current-voltage characteristic of a $Ta - Ta_2O_5 - Nb$ junction.

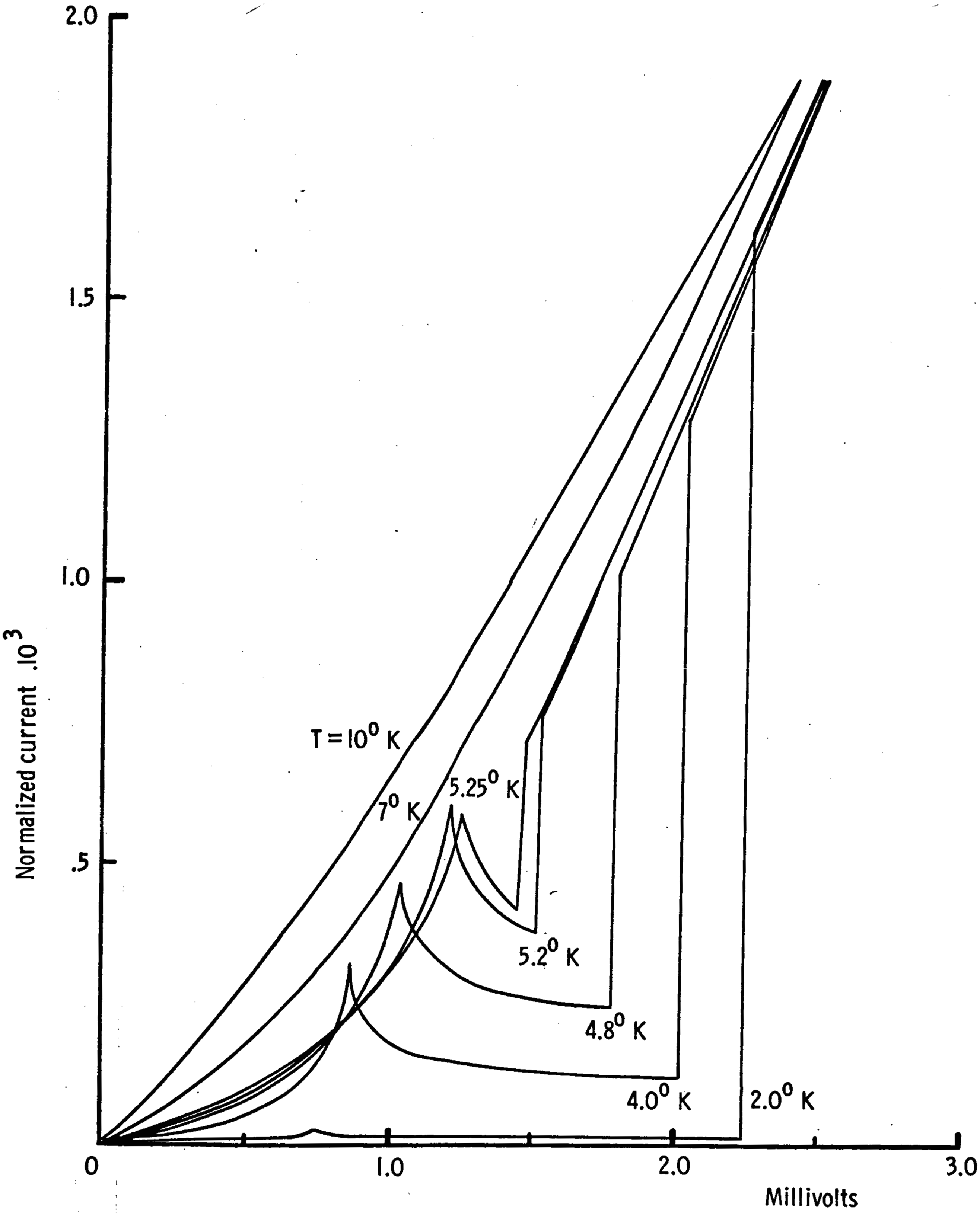


Figure 5.- Current-voltage characteristic of a Nb-Nb_2O_5-V junction.

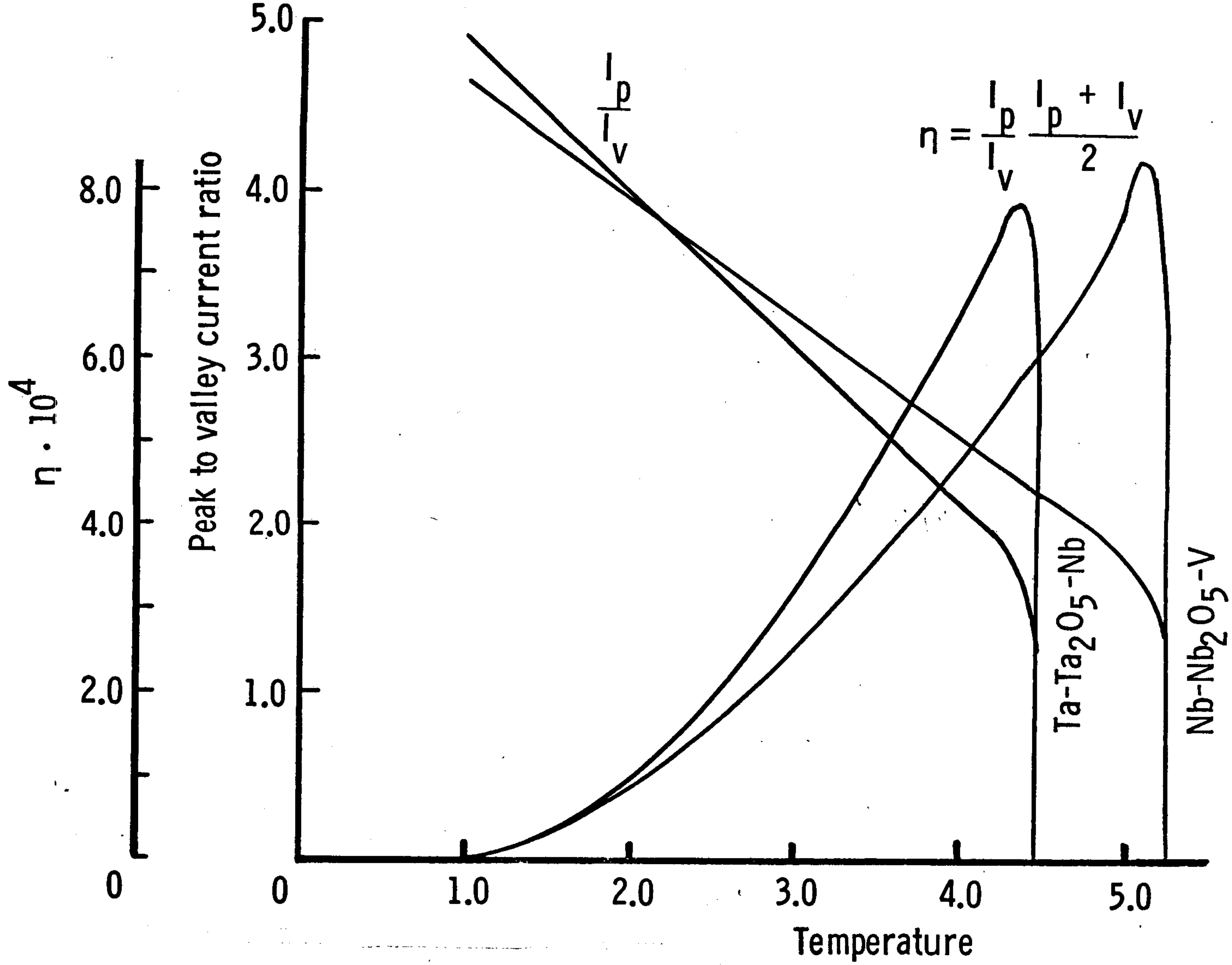


Figure 6.- Peak to valley current ratio versus temperature.

where I_p and I_v are the peak and valley currents, respectively. Fig. 6 also shows a plot of η as a function of temperature for both junctions. The curves are observed to peak in the vicinity of 4.4°K for the Ta-Ta_2O_5-Nb junction and 5.1°K for the Nb-Nb_2O_5-V junction.

An important problem that still remains is that of determining the actual current which will flow based on the physical properties of the junction (e.g., the thickness and dielectric constant of the insulating layer and the area of the junction). This problem has been studied in considerable detail and it is hoped that a solution will be obtained during the summer while the author is participating in the NASA-ASEE Summer Faculty Fellowship Program.

EXPERIMENTAL RESULTS

Efforts to verify the predicted behavior for both the Ta-Ta_2O_5-Nb and the Nb-Nb_2O_5-V junctions have not yet been successful. In the case of the Ta-Ta_2O_5-Nb junction the problem has been the inability to achieve superconductivity in the deposited tantalum film. The reason for this is believed to be the small size of the crystallites whose many boundaries prohibit the proper conditions for superconductivity. This trouble could probably be eliminated by increasing the deposition rate while using a heated substrate. Since the equipment required for this operation was not available, it was decided to temporarily halt work on this junction in favor of the Nb-Nb_2O_5-V junction.

Several niobium films have been deposited which readily became superconductive when immersed in liquid helium. However, after the oxidizing process, the superconducting properties were lost. It is strongly suspected that this behavior is caused by the annealing of the niobium at the high temperatures that are required during the oxidation process. The solution to this problem may be to find a different oxidation process.

CONCLUDING REMARKS

Since the work reported here is to be continued under the NASA-ASEE Summer Faculty Fellowship Program, a few comments regarding future work are in order. In regard to further theoretical development, the major emphasis should be placed on completing the study relating the actual current to the physical properties of the junction. After this problem is solved it will be a relatively simple matter to program the computer to find the numerical value of the negative resistance at a desired operating point. Once the negative resistance is known, it can be used in the design of the associated circuitry. Looking at it another way, if the operating conditions of the circuit are specified so that the desired value of the negative resistance is known, then a junction with the proper characteristics can be designed.

With regard to the experimental phase, special effort must be given to developing processes and techniques for fabricating the junction. Reliability and reproducibility are of great importance if the junction is to be used as a practical circuit element.

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