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## Superconducting Switch Program Final Report

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*Materials Physics Branch  
Material Science and Technology Division*

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# SUPERCONDUCTING SWITCH PROGRAM

## FINAL REPORT

This is the final report of work done to study the feasibility of a superconducting opening switch. This phase of the investigation considers the following : 1) The achievement of critical current densities of over  $10^7 \text{ A/cm}^2$  in NbN. 2) Determination of the power required to operate a superconducting switch. 3) Utilization of materials other than NbN in such a switch.

### (1.0) Introduction

Our initial work to demonstrate the feasibility of a superconducting opening switch was detailed in an NRL Memorandum report<sup>1</sup>. In that report we discussed our materials studies where preparation conditions such as sputtering pressure and substrate temperature were varied in an effort to optimize the product of the resistivity  $\rho$  and the critical current density  $J_C$ . We found that  $\rho$  and  $J_C$  were strongly dependent upon the sputtering conditions and we determined those conditions for which the product of these quantities was maximized. Subsequently it was realized that  $J_C$  was the more important quantity since  $\rho J_C^2$  was the maximum power available to the load. Consequently we focused our attention on obtaining the maximum  $J_C$  possible for NbN. In our earlier work we made measurements of switching speed at low currents. It was noted that the power required to operate the switch was on the order of the power switched. Consequently we studied the power needed to operate the switch as a fraction of current through the switch. We had been restricting our efforts to NbN for practical reasons but other materials such as Nb<sub>3</sub>Sn or, more recently, the high  $T_C$  oxides raise interesting possibilities which merit consideration.

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<sup>1</sup>Manuscript approved July 17, 1989.

## (2.0) Critical current density

In an earlier publication<sup>2</sup>, we presented work intended to demonstrate the feasibility of a superconducting opening switch. The current density and the resistivity both affect the utility of a superconducting switch.<sup>3</sup> Higher current densities allow the switch to carry more current. Higher normal state resistivities allow more current to be switched to the load. Films sputtered in our system were granular in character. The resistance of the films increased with decreasing temperature. This activated behavior is similar to that observed in semiconducting materials. In semiconductors the effect is attributed to thermal excitation of electrons from the valence band into the conduction band. In granular materials the electrons are prevented from moving freely because of the intergranular barrier.<sup>4</sup> As temperature is decreased, less thermal energy is available to the electrons, consequently they are less able to move from grain to grain and thus the resistivity increases.

The relationship between resistivity and critical current density in superconducting granular films may be described by a model developed by Kampwirth and Gray.<sup>5</sup> They hypothesized a material which consisted of spherical grains that were arrayed in a three dimensional cubic lattice and were interconnected by Josephson coupling. Using this model they derived an expression which shows that the critical current is directly proportional to the energy gap and inversely proportional to the product of the resistivity and the grain diameter. Selecting appropriate values for the energy gap, grain size, and resistivity the model indicates that current densities on the order of  $10^6 \text{A/cm}^2$  are possible. We note that for our films resistivity and critical current density are inversely related. This can be seen in figures 1 and 2. In general our films with the highest critical current density had the lowest resistivity. The lowest resistivity values were on the order of  $100 \mu\Omega\text{-cm}$ . The resistivity ratio of these films approached one. Since the maximum power available to the load is proportional to  $\rho J_c^2$ , the critical current density had more impact than the resistivity. Therefore we concentrated on optimizing the critical current density of our NbN switch element with  $1 \times 10^7 \text{A/cm}^2$  as a target value.

Our early materials optimization work was confined to planar films. This was a convenient geometry and allowed easy sculpting of films using standard photolithographic techniques into shapes with large current pads and a constricted current path. As a result the total current was kept low for easy laboratory measurements and the current density through the contacts was kept small which prevented excessive joule heating. The maximum  $J_c$  values we achieved were on the order  $10^6$  A/cm<sup>2</sup>. Variation of the preparation conditions did little to increase  $J_c$  above this value, so we began to look for other reasons why we were unable to achieve  $J_c$  values of  $10^7$  A/cm<sup>2</sup> reached in NbN by others.<sup>6</sup>

Transport current does not flow uniformly throughout a planar thin film whose dimensions are large compared to the penetration depth. The penetration depth of NbN is approximately 2800Å.<sup>7</sup> Maximum current flows at the edges and little in the middle of the film.<sup>8</sup> Edge effects can be avoided by using either a disk like structure where current flows radially after having been introduced at the center and removed at the periphery or vice versa<sup>9</sup> or by using a cylindrical structure with the current flowing along the long axis.<sup>10</sup> We chose the cylindrical geometry.

We prepared samples of NbN on small diameter quartz and sapphire rods, the results are shown in figure 3. There was an immediate improvement of  $J_c$  in going from planar to cylindrical substrate geometry. We also observed a further improvement by changing from quartz to sapphire substrate material as can be seen from the figure. A similar improvement in film quality had been noted in earlier work and was attributed to mechanical strain resulting from the use of different substrate material.<sup>11</sup> However in this case we note that crystalline sapphire has a better thermal conductivity at liquid helium temperatures than fused quartz and we believe this is responsible for the improved  $J_c$  values. The material with the highest  $J_c$  was prepared at argon pressures of approximately 10 microns with an additional 2-3 microns of nitrogen at power density levels of approximately 66 watts/cm<sup>2</sup>. The rod samples were heated by rotating them between a pair of rectangular parallelepipeds four inches long which were mounted parallel to each other about 1/4" apart and screwed to our molybdenum substrate heater table. This configuration enabled us to heat the rods from three sides during deposition to

temperatures of approximately 900C. The  $J_c$  values achieved are high enough to be of interest to switch designers but greater values, of course, are more desirable.

The preparation of NbN films of high critical current densities was achieved in our system by the use of low pressures and high temperatures. This was successful on a small scale. It is important to note that these conditions may be system specific. A larger system to deposit films on a large diameter sapphire cylinder might require other conditions to achieve the same result. Consequently the fabrication of a switch element for use in an engineering scale up would be an important study to be undertaken by someone with the capability of making such a large scale deposition.

### **(3.0) Power to operate a superconducting switch**

An experiment was set up to measure the laser power required to operate a superconducting switch. A mirror in the shape of the interior surface of the frustum of a cone was machined from brass, polished and chrome plated. This mirror which had a two inch aperture with a one-half inch hole was mounted on a cryostat which could then be immersed into liquid helium. The NbN clad fiber was placed parallel to the axis of the conical mirror such that a beam of light parallel to the axis would be intercepted by the wide aperture of the mirror and focused onto the fiber and impinge at normal incidence. The fiber was longer than the height of the frustum and so protruded beyond the mirror on both sides. The current leads used to hold the fibers in place were ribbon like and arranged to intercept as little light as possible. Separate voltage leads were used to sense when the fiber was driven into the normal state. The laser power was set and the current through the sample increased until a voltage was observed. This point was taken as the laser power necessary to operate the switch at that value of critical current. This was repeated for several values of laser power.

The results of our measurements are shown in figure 4. The energy values plotted are those incident upon the dewar window measured at the room temperature surface of the dewar. In order to estimate the value of energy

absorbed by the sample we made the following estimates. We assumed that 4% of the incident light was reflected from each window surface. There were two windows for a total of four surfaces so 84% was transmitted. We further assumed the mirror transmitted 90%, and the sample absorbed 10% while approximately 20% of the light was scattered from the liquid because of bubbles and turbulence. In addition there was a geometric factor of 0.56 to take into account the ratio of the area of the incident beam to the area of the beam intercepted by the reflector, and another geometric factor of 12.56 to take into account the increase in intensity due to the focusing of the large diameter laser beam onto the small diameter fiber. When all this is combined we find the actual energy absorbed by the sample is approximately 0.4 times the incident energy plotted in figure 4.

The general trend of the data indicates that, when the material is carrying a current close to its maximum critical current density, very little external energy is required to drive it normal. The rapid increase in laser power required at lower  $J_c$  values however was unexpected. An explanation for this was suggested by the time scales involved. The laser pulse was approximately 12nsec wide, but the switch was found to remain normal for approximately 100nsec. This suggested that the sapphire rod as well as the film was warming up from 4.2K to some transition temperature characteristic of NbN carrying a fraction of  $J_c$ . The energy absorbed by the sample was on the order of microjoules, while the condensation energy of the superconducting material illuminated by the laser was on the order of nanojoules. We explain this discrepancy in the following way. We can approximate the data for the low temperature specific heat of sapphire<sup>12</sup> from 5K to 95K by the equation  $C_p(T) = 1.08 \times 10^{-8} T^{3.24}$  calories/gramK. Using this equation we can estimate the energy necessary to raise the temperature of the sapphire rod from 4.2K to 15K. This turns out to be on the order of microjoules which is comparable to the energy absorbed by the sample. This suggests that the thermal coupling between the substrate and the superconductor is so strong that both must be raised above  $T_c$  in order for the switch to operate.

From figure 4 we note that, as the current carried by the film approaches the critical current density of the superconductor, the laser energy required to drive the superconductor normal decreases. It is possible that energy gain can

be realized, (more energy can be switched than is used to operate the switch). A superconducting opening switch in parallel with a load when driven normal would divert current to the load. The optimum power transfer would occur when the impedance of the load is equal to that of the switch. In this case the current  $I_s$  would be split between the load and the switch. The maximum power available to the load would be  $R_s(I_s/2)^2$ . The duration of the pulse at half amplitude was approximately 100nsec. If we take for  $R_s$  the resistance of that portion of the film that is driven normal by the laser, we may estimate the energy available to the load. This data is plotted together with the incident laser energy in figure 5. We note the load energy increases with current while the laser energy needed to trigger the switch decreases. At  $J_c$  the laser energy required is zero. A single superconducting switch may be operated this way. However if many superconducting switch elements are needed to provide the required current, a laser would be necessary to fire the switches simultaneously. The desirable situation would then be to operate close enough to  $J_c$  so that very little energy is needed to fire the switch but not so close that some event would prematurely activate the switch (or an element of the switch in a complex configuration).

It is interesting to note that the thermal conductivity of sapphire increases from approximately 3 watts/cmK at 4.2K to 100 watts/cmK at 15K. Not only does the increase of specific heat augment the energy required to drive the switch normal but also more energy is required due to the increase in conductivity. We also note that careful selection of the mass of the substrate as well as how hard it is driven thermally can be advantageous in extending the output pulse duration. Also the improved thermal conductivity could aid in the recovery of the switch so that, once the laser is turned off, the heat can be quickly dissipated.

#### **(4.0) Use of materials other than NbN**

Our initial concept of a superconducting opening switch was a device that would operate at liquid helium temperatures. NbN was selected because it was a durable material that was easy to deposit. In addition we had the experience and facilities to make high quality films of this material. With the

discovery of new materials, old applications are invariably reviewed and this application is no exception. The discovery of the high- $T_c$  oxides appears to provide many options which earlier designs did not have. Liquid nitrogen is less expensive and easier to handle than liquid helium and if critical current densities can be increased these materials might have interesting potential for use as a switch. Realizing that in our experiments with a low  $T_c$  superconductor most of the triggering energy went into heating the sapphire rod as well as the superconductor, we estimate the energy that would be required by a switch operating at liquid nitrogen temperatures.

An estimate of the energy needed to operate a superconducting opening switch can be obtained by calculating the condensation energy and the thermal energy needed to raise the material and the rod from its operating temperature to above its transition temperature. From the following equations  $H_c^2/8\pi = 1/2 [N(E_F) \Delta^2]$  and  $\Delta/kT_c = 1.764 \delta^{13}$  along with  $\gamma = (1/3\pi^2)N(E_F)k^2(1+\lambda)$ <sup>14</sup> we may obtain an expression for the condensation energy in terms of fundamental material parameters shown in the following equation

$$\frac{H_c^2}{8\pi} = 0.473 \gamma \delta^2 T_c^2 / (1 + \lambda) \quad (1)$$

where  $\gamma$  is the electronic coefficient of specific heat,  $\delta$  the strong coupling gap scaling parameter,  $\lambda$  the electron-phonon coupling parameter, and  $T_c$  the transition temperature. An expression for the energy necessary to raise the superconductor from its operating temperature to above its transition temperature can be obtained by integrating the sum of the electronic and lattice contributions to the specific heat. The result is given by the following equation

$$E = \frac{\gamma(T_c^2 - T_{op}^2)}{2} + \frac{12 \pi^4 n k (T_c^4 - T_{op}^4)}{20 \theta_D^4} \quad (2)$$

where  $n$  is the number of atoms per cubic centimeter,  $\theta_D$  the Debye temperature, and  $k$  Boltzmann's constant.

For NbN,  $\gamma = 4.7 \times 10^3$  ergs/cm<sup>3</sup> K<sup>2</sup>,  $T_c = 15$ K,  $\theta_D = 350$ K,  $n = 9.4 \times 10^{23}$  at.ms/cm<sup>3</sup>,  $k = 1.38 \times 10^{-16}$  ergs/K. If we take both  $\lambda$  and  $\delta$  to be 1.0 then equation (1) gives  $2.5 \times 10^5$  ergs/cm<sup>3</sup> for the condensation energy and equation (2) gives  $4.9 \times 10^5$  ergs/cm<sup>3</sup> for the thermal energy. Integrating the expression we gave earlier for the specific heat of sapphire over the temperature range 4.2K to 15K we find that the thermal energy required by the sapphire substrate is  $4.1 \times 10^4$  ergs/cm<sup>3</sup>. Doing a similar calculation for Y-Ba-Cu-O we estimate  $\gamma$  to be  $2.5 \times 10^3$  ergs/cm<sup>3</sup> K<sup>2</sup>,  $\delta$  is approximately 1.0,  $\lambda$  is about 3.0, and  $T_c$  is 90K. Equation (1) gives a condensation energy of  $2.4 \times 10^6$  ergs/cm<sup>3</sup>. The thermal energy is obtained by integrating the specific heat  $C_p(T)$  obtained in the literature<sup>15</sup> from 77K to 90K. This gives  $1.2 \times 10^8$  ergs/cm<sup>3</sup>. The energy required to raise the temperature of the sapphire over this interval may be found as before and is  $4.1 \times 10^7$  ergs/cm<sup>3</sup>.

In order to make a comparison between the NbN and the high  $T_c$  oxides lets assume we have a 0.1cm diameter sapphire rod 1.0cm long with a uniform one micron ( $1.0 \times 10^{-5}$ cm) layer of superconductor on the cylindrical surface. The sapphire volume would be  $7.9 \times 10^{-3}$  cm<sup>3</sup> while the superconductor volume would be  $3.1 \times 10^{-5}$  cm<sup>3</sup>. The NbN would require 23.3ergs to overcome the condensation energy and raise it from 4.2K to 15K while the sapphire substrate would require 321ergs. The Y-Ba-Cu-O would require  $3.8 \times 10^3$  ergs to overcome the condensation energy and raise it from 77K to 90K while the sapphire substrate would require  $3.1 \times 10^5$  ergs. The heat capacity of the sapphire is a problem at 4.2K but it is an even greater one at 77K. The utility of this material in a superconducting opening switch is questionable at least until reproducible high  $J_c$  values can be achieved. It appears necessary, due to energy switching considerations, to operate the high- $T_c$  oxide superconductors much closer to the  $J_c$  switching point.

The choice of NbN for this study was one of convenience. Our group had considerable experience with this material and the facilities to prepare it under various conditions and to study the effect of these conditions on the material. If further work is to be done on a superconducting switch, other materials such as Nb<sub>3</sub>Sn, V<sub>3</sub>Ga, or other A15 materials should be considered as candidate materials. The critical current densities available would be higher than those of NbN, and preparation might not be much more difficult. For example, a

sputtered niobium film on a cylindrical substrate could be reacted in an evacuated sealed quartz tube containing small amounts of tin. Unlike multifilamentary wire, these A15 films need no swaging or drawing so their brittleness or other metallurgical properties considered detrimental to wire fabrication would be no problem in this application and one could take full advantage of their better superconducting properties.

### **(5.0) Single shot configuration (exploding switch)**

The switch element that has been considered up to this point has been one that could be operated in a nondestructive repetitive mode. However in some instances there could be advantages to a superconducting opening switch operating in a single shot mode where the element is destroyed and must be replaced after one use. Such a device was suggested by a colleague at a recent meeting.<sup>16</sup> Present techniques of interrupting a large current flow consist of using explosives on a large copper bus bar. While this works, there is a tendency toward arcing so that the current interruption is not a clean step function.

A superconducting film on a frangible sapphire cylindrical substrate would seem to be ideal for such a purpose. A hollow sapphire substrate could contain an explosive charge or exploding wire which when detonated would shatter the cylindrical substrate into many fragments. The result would be many resistors in series so that each boundary between shards would only see a small fraction of the total voltage drop across the switch. Consequently the switch would open with no arcing provided there was a proper choice of parameters and the result would be a clean step function. The open state resistance of this switch would be very high. This would result in a much larger  $\rho J_c^2$  value than could be otherwise realized. Because the open state resistance would be so high due to the mechanical separation of the shattered film, one could concentrate on using material with the highest  $J_c$  available.

This technique could be used for all the materials (B1, A15, or high- $T_c$  oxide) discussed in this paper. In addition the energy penalty due to the thermal mechanism of activation would no longer be a consideration.

## **(6.0) Other switching mechanisms**

The superconducting opening switch we have discussed up to now has relied on thermal heating to activate the switch. As we have seen this imposes restrictions upon the operating conditions such as being close to  $J_c$  to achieve efficient operation. It is possible to select a laser frequency to achieve greater absorption efficiencies, and hence decrease the required laser power. For example metallic compounds of transition metals generally absorb light of shorter wavelengths better than longer wavelengths. Consequently, an ultraviolet laser might couple more energy into the material and so enhance the efficiency of a thermal process, rather than the visible light laser (532nm) used in this study.

Experiments to study the laser induced superconducting to normal transition in thin lead films gave results that could not be explained by thermal effects<sup>17</sup>. Further studies showed that laser irradiation of lead films could induce an intermediate state whose dynamics were influenced by movement of the superconducting normal boundaries<sup>18</sup>. It is possible that effects other than thermal effects might be observable in our films. Perhaps a laser with a frequency near the gap frequency might cause direct pair breaking without heating of the material and thus operate the switch. Such a nonequilibrium mechanism if it existed would only need to overcome the condensation energy in the operation of a superconducting opening switch and offers the possibility of large energy gain and fast operating times. Such considerations should be explored. If realized such a nonequilibrium method would allow the use of high  $T_c$  oxide superconductors as switches without the energy penalty discussed earlier.

## **(7.0) Conclusions**

In our studies we have investigated the characteristics of a laser operated superconducting opening switch and have shown that such a switch is feasible. The utility of such a switch would be improved if it could be operated

at greater current densities. We have used NbN and achieved values of  $10^7 \text{A/cm}^2$ , but other materials such as  $\text{V}_3\text{Ga}$  or  $\text{Nb}_3\text{Ge}$  offer the possibility of ever higher current densities in a region where specific heat penalties are small. This does not completely rule out the use of the high- $T_c$  oxides if they could be operated by a laser near the gap frequency. This would allow direct pair breaking without heating. If a repetitive switch is not required, superconductors could be used as a high current explosive opening switch having the advantages of opening rapidly and cleanly. This would also be a way of avoiding problems related to heat capacity.

### **(8.0) Acknowledgements**

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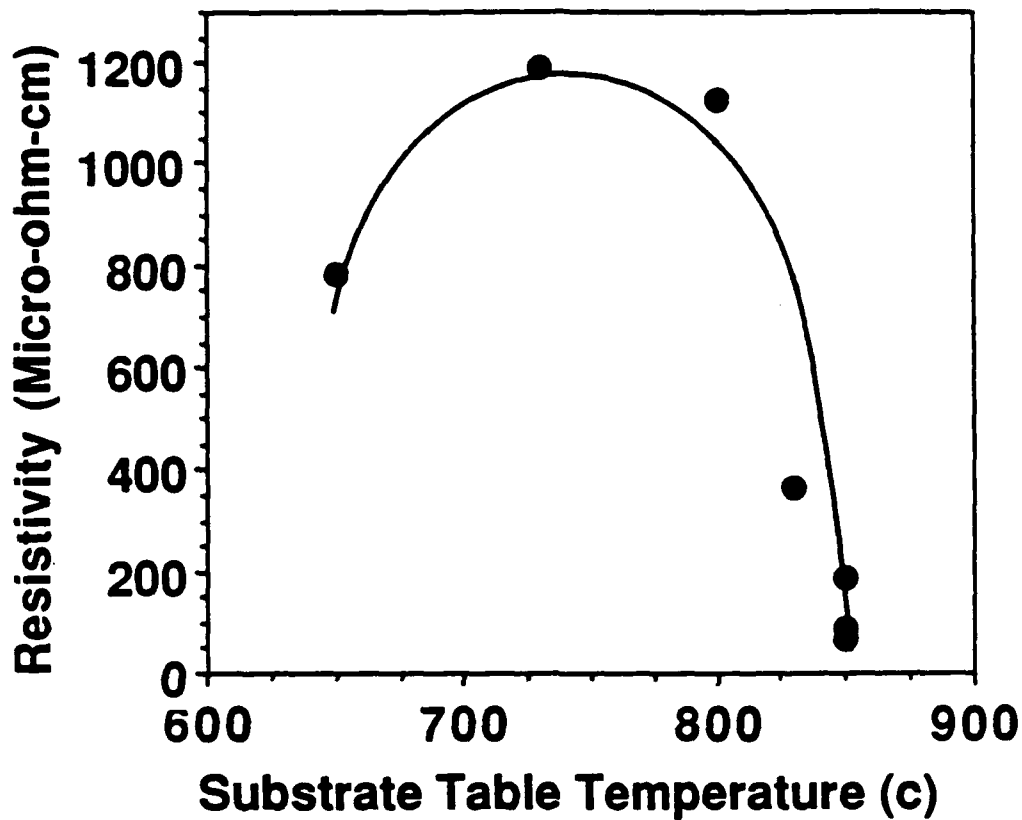


Figure 1. Resistivity just above the transition temperature for the same NbCN films shown in figure 2. Films having the smallest resistivity values also have the largest critical current values as described by the model discussed in the text. The line shown is not a theoretical curve but intended to indicate the trend of the data.

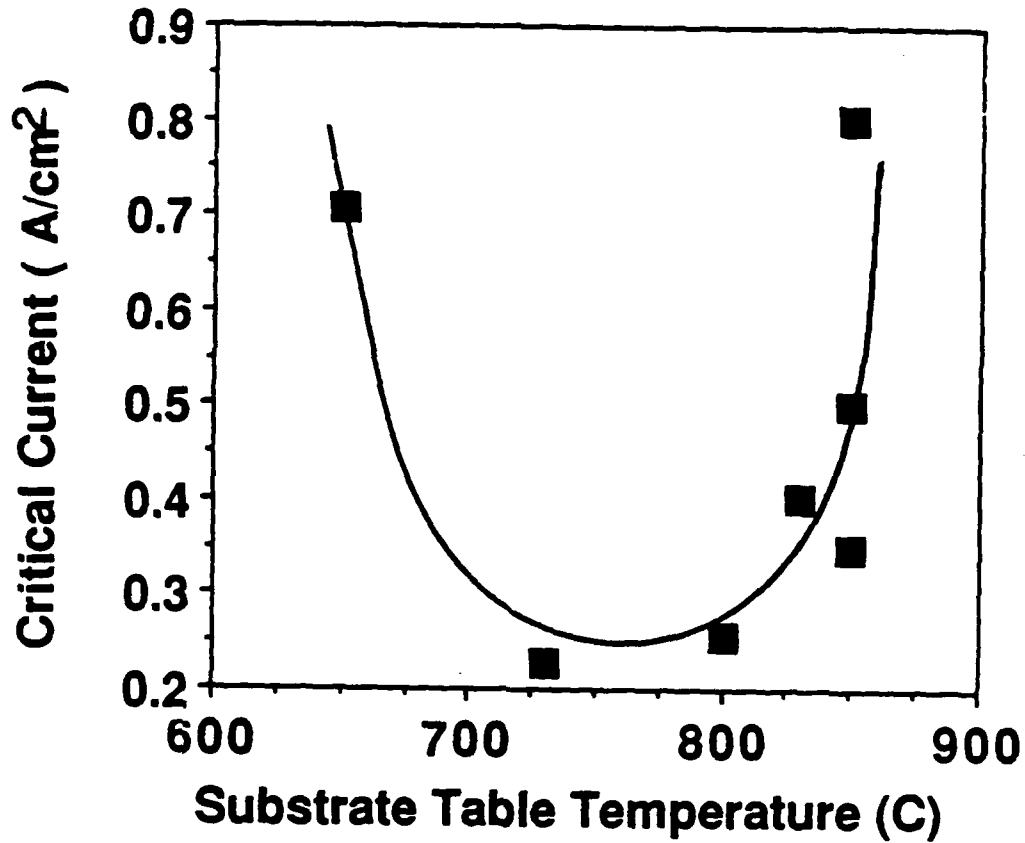


Figure 2. Critical current density at 4.2K as a function of substrate table temperature for the same NbCN films shown in figure 1. The highest substrate temperatures resulted in the greatest critical current densities, and the lowest resistivities as described by the model discussed in the text. The trend in the data is shown by the curve which is not a theoretical curve.

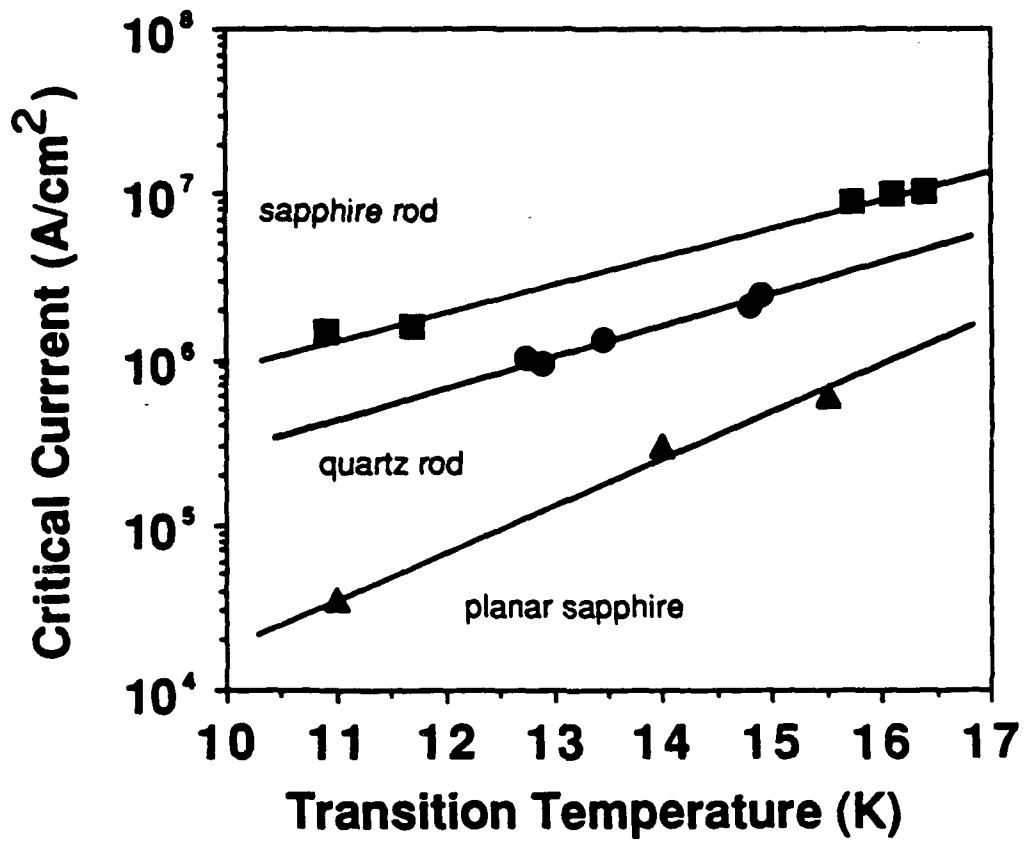


Figure 3. Critical current density as a function of critical temperature for different substrate geometries and materials. The lines shown are intended as a guide to the eye.

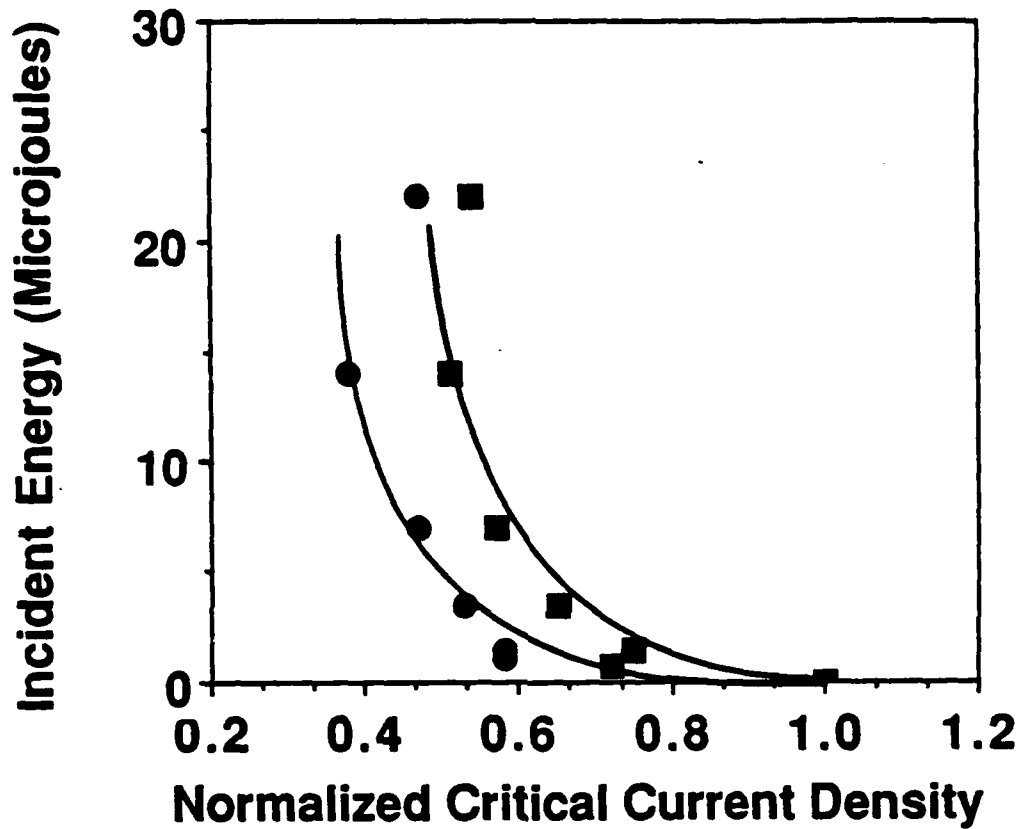


Figure 4. Incident laser energy required to open the switch at 4.2K as a function of normalized current flowing through the switch. The lines shown are intended as a guide to the eye.

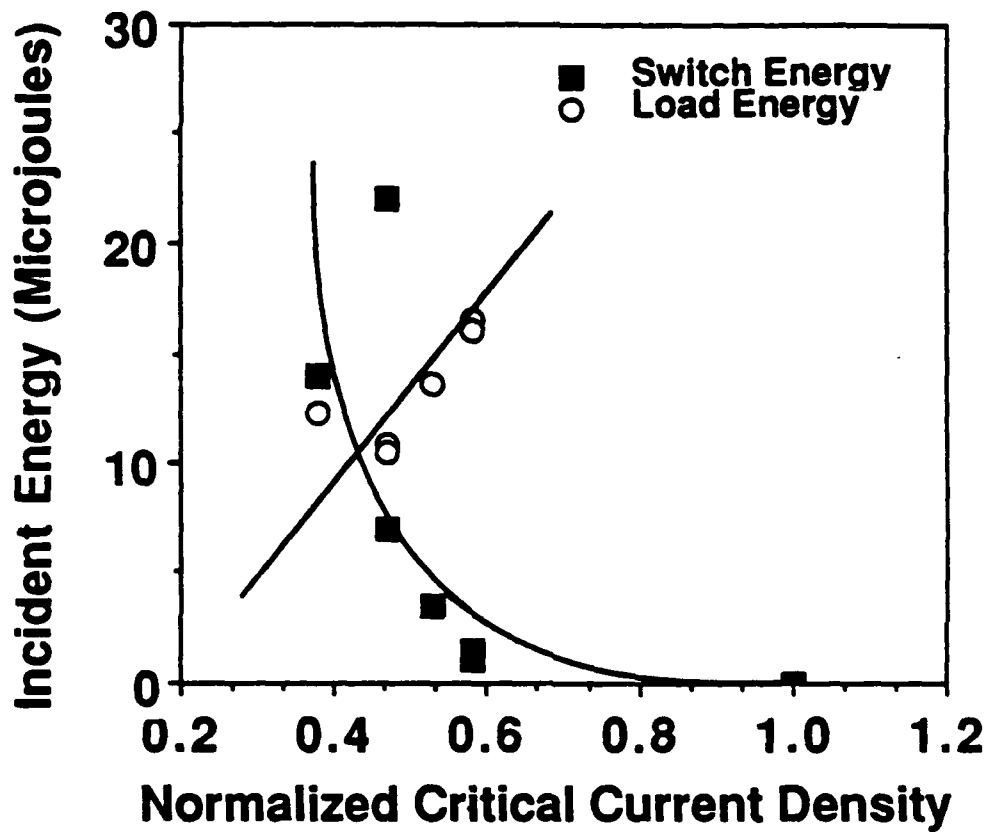


Figure 5. Incident laser energy and the energy available to the load as a function of normalized current flowing through the switch at 4.2K. The lines shown are intended as a guide to the eye.