We have prepared NbN films on planar sapphire, and on small diameter cylindrical quartz and sapphire substrates. Films prepared on cylindrical substrates had a greater critical current density than those prepared on planar substrates. Our highest current densities of \(1 \times 10^7\) A/cm\(^2\) were achieved on cylindrical sapphire substrates. Measurements of the laser power required to drive the switch into the normal state were made as a function of current being carried by the NbN clad sapphire rod. These experiments indicated that near \(J_c\) very small amounts of laser energy were needed to drive the sample normal as expected. At current values well below \(J_c\) much larger energies were required. These large energies, which are roughly \(10^3\) larger than the condensation energy, were attributed to heating of the sapphire rod necessary to raise the NbN above its transition temperature. The desirable properties of a superconducting switch are the ability to carry large currents in the superconducting state and have a high resistance in the normal state. Considerations for using the high-\(T_c\) oxides in a superconducting switch are examined.

**Introduction**

In an earlier publication\(^1\), we presented work intended to demonstrate the feasibility of a superconducting opening switch. Consequently we focused our efforts on demonstrating that a superconducting film could indeed be switched momentary into the normal state and, when the laser was switched off, revert to the superconducting state. We concerned ourselves primarily with the material parameters of the NbN film and explored preparation conditions which would optimize critical current density and resistivity. In this paper we explore several issues that came to light as a result of our earlier work. These are optimization of the critical current density, determination of the power needed to operate a switch, and the significance of the new class of high-\(T_c\) oxide superconductors on such a switch. The current density is one parameter that impacts heavily on the usefulness of a superconducting switch.\(^2\) The greater the current the more useful the switch. Therefore we concentrated on optimizing the critical current density of our NbN switch element with \(1 \times 10^7\) A/cm\(^2\) as a target value. The power necessary to trigger the superconducting switch was of interest since our earlier work indicated that it was comparable to the power that was switched. Consequently we made some measurements to determine the laser power necessary to quench the superconductor at various fractions of \(J_c\). The new high-\(T_c\) oxides have presented new possibilities for consideration in the design of a superconducting opening switch. We offer some thoughts on how these new materials might affect this application.

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   Naval Research Laboratory, Washington D.C., 20375

2. R. A. Hein
   Department of Physics
   The Catholic University of America Washington D.C. 20064

**Abstract**

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\(^2\). 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\(^2\) reached in NbN by others.\(^3\)

Transport current does not flow uniformly throughout a planar thin film whose dimensions are large compared to the penetration depth. The penetration depth is approximately \(2800\)A.\(^4\) Maximum current flows at the edges and little in the middle of the film.\(^5\) 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\(^6\) or by using a cylindrical structure with the current flowing along the long axis.\(^7\) We chose the cylindrical geometry.

We prepared samples of NbN on small diameter quartz and sapphire rods. The results are shown in figure 1. 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.\(^8\) However in this case we note that crystalline sapphire has a better thermal conductivity at liquid helium temperatures than fused quartz and 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\(^2\). 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 ¼" 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 900°C. The \(J_c\) values achieved are high enough to be of interest to switch designers but greater values of course are more desirable.

**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 NbN clad sapphire rod 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
all this is combined we find the actual energy absorbed by the sample is approximately 0.4 times the incident energy plotted in figure 2.

![Figure 1: Critical current density as a function of critical temperature for different substrate geometries and materials. The line shown is intended as a guide to the eye.](image1)

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 on the order of 12nsec wide, however the switch was found to be 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 can approximate the data for the low temperature specific heat of sapphire 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 because of the close thermal coupling between the substrate and the superconductor both must be raised above $T_c$ for the switch to operate.

![Figure 2: Incident laser energy necessary to quench the superconducting switch as a function of normalized current flowing through the switch.](image2)
From figure 2 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 $P_s(I_s/2)^2$. The duration of the pulse at half amplitude was approximately 100 nsec. 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 3. 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 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 because of 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.

**Impact of the high-$T_c$ oxides**

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 frequently reviewed and our 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 a large fraction of triggering energy went into heating both the sapphire rod as well as the superconductor, we attempted to 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 $H_{c2}/8\pi = 1/2 [N(E_F) \Delta^2]$ and $\Delta/kT_c = 1.764 \delta^{10}$ along with $\gamma = (1/3\pi^2)N(E_F)k^2(1+\lambda)\delta^{11}$ we may obtain an expression for the condensation energy in terms of fundamental material parameters shown in the following equation:

$$\frac{H_{c2}^2}{8\pi} = 0.473 \gamma \delta \frac{\Delta^2}{T_c^2}(1+\lambda)$$  \hspace{1cm} (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:

$$E = \gamma \left( T_c^2 - T_{op}^2 \right) + \frac{12\pi^4 n k \left( T_c^4 - T_{op}^4 \right)}{20 \theta_D^2}$$ \hspace{1cm} (2)

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

For NbN, $\gamma = 4.7 \times 10^3$ ergs/cm$^3$ K$^2$, $T_c = 15K$, $\theta_D = 350K$, $n = 9.4 \times 10^23$ atoms/cm$^3$, $k = 1.38 \times 10^{-16}$ ergs/K. If we take both $\lambda$ and $\delta$ to be 1.0 then equation (1) gives $2.6 \times 10^5$ ergs/cm$^3$ for the condensation energy and equation (2) gives $4.9 \times 10^5$ ergs/cm$^3$ 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 $4.1 \times 10^4 \text{ergs/cm}^3$. Doing a similar calculation for Y-Ba-Cu-O we estimate $y$ to be $2.5 \times 10^3 \text{ergs/cm}^3 \cdot \text{K}^2$, $\delta$ is approximately 1.0, $\lambda$ is about 3.0, and $T_c$ is 90K. Equation (1) gives a condensation energy of $2.4 \times 10^6 \text{ergs/cm}^3$. The thermal energy is obtained by integrating the specific heat $C_p(T)$ obtained in the literature$^{12}$ from 77K to 90K. This gives $1.2 \times 10^6 \text{ergs/cm}^3$. The energy required to raise the temperature of the sapphire over this interval may be found as before and is $4.1 \times 10^7 \text{ergs/cm}^3$.

In order to make a comparison let's assume we have a 0.1cm diameter sapphire rod 1.0cm long with a uniform one micron (1.0X10^{-5} cm) layer of superconductor on the cylindrical surface. The sapphire volume would be $7.9 \times 10^{-3} \text{cm}^3$ while the superconductor volume would be $3.1 \times 10^{-5} \text{cm}^3$. 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 $3.8 \times 10^3 \text{ergs}$ to overcome the condensation energy and raise it from 77K to 90K while the sapphire substrate would require $3.1 \times 10^5 \text{ergs}$. The heat capacity of the sapphire is a problem at 4.2K but it is an even bigger problem 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.

**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 is improved if it could be made to operate at greater current densities. We have used NbN, but other materials such as V$_3$Ga or Nb$_3$Ge offer the possibility of 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. Such a nonequilibrium mechanism would only need to overcome the condensation energy and offers the possibility of large energy gain and fast operating times if it can be realized.

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