n-InAs/GaAs heterostructure superconducting weak links with Nb electrodes

IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598

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We report on the fabrication and characterization of planar superconductor-normal-superconductor (SNS) weak links in which the normal region is deposited n-InAs. The InAs is part of a heterostructure consisting of 100 nm of n-InAs grown on an undoped GaAs buffer layer on a semi-insulating GaAs substrate. The superconductor is Nb, patterned by electron beam lithography with interelectrode spacings as small as 260 nm. Device behavior is well explained by SNS weak link theory, with coherence lengths calculated from measured material parameters. These heterostructure weak links can be the basis for superconducting field-effect devices. They have the significant advantage of allowing simple device isolation compared with bulk InAs, which has been used in previous attempts to make such devices.

Recognition of the need for three-terminal devices for cryogenic circuit applications has resulted in renewed interest in superconducting field-effect transistors (FET's), which were first proposed a number of years ago. These are superconductor-normal-superconductor (SNS) weak links in which the link is a semiconductor, allowing the strength of the Josephson coupling (i.e., the supercurrent) to be controlled by adjusting the carrier concentration in the link (or FET channel) via a gate.

The original superconducting FET proposals emphasized the use of materials such as InAs for the channel because, in these materials, the pinning of the Fermi level in the conduction band at surfaces and interfaces results in Schottky barrier-free contacts; the presence of such barriers in a superconducting FET device would decrease the maximum available supercurrent, reduce the degree of control of the supercurrent via the gate, and represent a significant series resistance in the device. Both Si and InAs have been used in the recent superconducting FET experiments. The absence of Schottky barriers, low effective mass, and high carrier mobility in InAs allow significantly larger device lengths and/or lower dopings for InAs compared with Si (for a given Josephson critical current). However, the InAs devices have two major drawbacks, namely, very poor response to applied gate bias and lack of device isolation. The application of several volts to the gate of a Nb/p-InAs/Nb device changes the critical current or device resistance by several orders of magnitude. For comparison, in the weak link experiment on bulk n-InAs,8 mobilities of 16,900 and 10,000 cm2/V s for dopings of 2.5 X 1017 and 2.6 X 1018 cm−3 were reported. The mobilities in the lightly doped layers were below those expected for bulk InAs, possibly due to defects resulting from the large lattice mismatch; however, growths on lattice-matched substrates (e.g., p-InAs) for comparison have...
Lisstrate. Also, channel thickness could be controlled by the electrodes (device lengths) ranged from \(0.26 \mu m\) to 3 \(\mu m\). The Hall-effect results down to the smallest gaps, indicating that the contact resistance was quite low. Supercurrents were obtained in the same way, but using \(T_c = 6.8 K\), which is the normal metal coherence length.

The critical current of a semiconductor-coupled SNS weak link varies with device length \(L\) as \(\exp(-L/\xi_N)\), where

\[
\xi_N = (\hbar^2/6\pi^2m_eT_c)^{1/2}(3\pi^2n)^{1/3}
\]

(1) is the normal metal coherence length \((\mu, m, n)\) are the electron mobility, effective mass, and density in the semiconductor). The \(I_c R_N\) product for SNS weak links was obtained by Likharev. For long links \((L > \xi_N)\) not too far from \(T_C\),

\[
I_c R_N = [4\Delta^2(T)/\pi e \nu T_c \xi_N^2] e^{-L/\xi_N},
\]

where \(I_c\) is the maximum Josephson supercurrent and \(R_N\) is the normal state resistance.

At low temperatures, the temperature dependence of the critical current is dominated by the \(T^{-1/2}\) variation of \(\xi_N\) and is therefore very sensitive to \(L/\xi_N\), providing a good method for determining \(\xi_N\) (fits to the data become very poor if the \(L/\xi_N\) ratio deviates by more than \(\approx 10%\) from the value used for an optimum fit). Figure 1 is a plot of the temperature dependence of critical current for the shortest link \((L = 0.26 \mu m)\). Fitting the low-temperature data (below \(\approx 4 K\)) to the temperature dependence implied by Eq. (2) gives a value of 4.35 for \(\Delta = \Delta (4.2 K) = 0.060 \mu m\) from Eq. (1), using the measured values of mobility and carrier density for this wafer, requires an effective mass of 0.048 for the InAs. The textbook value \(\nu T_c = 0.023\); however, at \(3.5 \times 10^{17} \text{cm}^{-3}\) the Fermi level is well into the conduction band, and the effective mass is larger than the value at the band minimum, and the value 0.048 is not unreasonable. The dashed line in Fig. 1 is a fit to the data using the temperature dependence of Eqs. (1) and (2), using \(L/\xi_N (4.2 K) = 4.35\) and a prefactor chosen to fit the data at 1.4 K. The data drop significantly below the theory curve above \(= 4 K\). This sort of deviation is common in SNS junctions, and may be related to the proximity effect on the superconductor.

The solid line in the figure was obtained in the same way, but using \(T_c = 6.8 K\), the temperature at which the observed critical current disappears; this lower \(T_c\) presumably represents the transition temperature of the SN bilayer. Note, however, that the electrode \(T_c\) is 8.84 K; at this temperature the \(I_c V\) characteristic changes resistance dramatically as large areas of Nb go normal. Thus, the meaning of the lower \(T_c\) is not completely clear.

Figure 2 is a plot of critical current (divided by electrode width) as a function of device length. The solid circles are our data, while the open circles were obtained from Ref. 8 from links on bulk \(n\)-InAs with essentially the same doping (the data given in that paper were for 2 K; the 4.2 K values were obtained from the known temperature dependence). There appears to be some consistency between the two experiments. Unfortunately, although all of the data in the figure are for essentially the same doping, the coherence lengths for the bulk sample and our thin InAs sample are different, due to the differing mobilities. The two lines in the figure are included to show consistency with the expected \(\exp(-L/\xi_N)\) dependence (the lines are drawn arbitrarily

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**Figure 1.** Temperature dependence of critical current for a weak link on \(3.5 \times 10^{17} \text{cm}^{-3}\) \(n\)-InAs. The low-temperature dependence, dominated by the \(T^{-1/2}\) dependence of \(\xi_N\), is sensitive to the value of \(L/\xi_N (T_c)\). A value of 60 nm is obtained for \(\xi_N\) at 4.2 K. The curves are fitted to the data using Eq. (2) with an adjustable prefactor. \(T_c\) values of 8.84 and 6.8 K were assumed for the dashed and solid curves, respectively. The inset is a schematic diagram of the device structure. The InAs and Nb layers are 100 and 60 nm thick, respectively, and link length \(L\) is as small as 260 nm.

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**Figure 2.** A plot of critical current (divided by electrode width) as a function of device length. The solid circles are our data, while the open circles were obtained from Ref. 8 from links on bulk \(n\)-InAs with essentially the same doping (the data given in that paper were for 2 K; the 4.2 K values were obtained from the known temperature dependence). There appears to be some consistency between the two experiments. Unfortunately, although all of the data in the figure are for essentially the same doping, the coherence lengths for the bulk sample and our thin InAs sample are different, due to the differing mobilities. The two lines in the figure are included to show consistency with the expected \(\exp(-L/\xi_N)\) dependence (the lines are drawn arbitrarily

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**TABLE 1.** Values of mobility and carrier density used in the calculation of the effective mass. The data are for our InAs, while the solid circles were obtained from Ref. 8 for bulk \(n\)-InAs. The solid line in the figure was obtained in the same way, but using \(T_c = 6.8 K\), the temperature at which the observed critical current disappears; this lower \(T_c\) presumably represents the transition temperature of the SN bilayer. Note, however, that the electrode \(T_c\) is 8.84 K; at this temperature the \(I_c V\) characteristic changes resistance dramatically as large areas of Nb go normal. Thus, the meaning of the lower \(T_c\) is not completely clear.
through data points; only the slopes are relevant). The values of $\xi_N$ used were 0.14 $\mu$m for the bulk sample\(^8\) (dashed line) and 0.060 $\mu$m for our sample (solid line).

The $I_C R_N$ product at 4.2 K is shown in the inset to Fig. 2. The $R_N$ values are the differential resistances at voltages large enough that the $I$-$V$'s are linear, $\approx 10$ mV. The solid curve is the theory of Likharev [Eq. (2)], with $\xi_N$ (4.2 K) = 0.060 $\mu$m and no adjustable parameters. The agreement with the data is remarkable in that we know of no case in which the full theoretical value of $I_C R_N$ was obtained experimentally for an SNS junction. In fact, there is some argument as to the validity of Likharev’s result.\(^9\) Clearly studies of more samples having different dopings would be very useful.

In summary, we have grown thin InAs layers on semi-insulating GaAs substrates with a wide range of dopings and reasonable mobility values. SNS weak link devices fabricated on a $3.5 \times 10^{17}$ cm$^{-3}$ $n$-type sample demonstrate that critical currents comparable to those obtained with bulk InAs devices can be achieved, with the advantages of easy device isolation and channel thickness control. Device behavior can be understood with simple SNS weak link theory. The $I_C R_N$ values obtained in this work are quite high, suggesting that semiconductor-coupled Josephson SNS weak links are indeed promising. This structure is intended to be applicable to low voltage FET devices, and should lead to modulation-doped superconducting FET’s and other similar devices.

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\(^12\)A. W. Kleinsasser (unpublished).