Scaling magnetoresistance induced by superconducting contacts in *n*-type GaAs

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A low-temperature ($T < 4.2$ K) transport study of *n*-type doped ($\simeq 10^{19}$ cm^{-3}) bulk GaAs reveals an enhancement of the electrical resistance, $\Delta R/R \simeq 10^{-3}$, below a critical temperature, $T_c = 3.4$ K, at low magnetic fields, $B < 30$ mT, when superconducting In point contacts are used as the current and voltage probes. The resistance correction is shown to be a homogeneous function of the magnetic field, B, and the reduced temperature, $\tau = (T_c - T)/T_c$, as $[\Delta R(T,B)/R]_s = A\tau^\kappa f(B/\tau^\beta)$ with $\kappa = 1.00 \pm 0.25$, and $\beta = 1.00 \pm 0.33$, in the vicinity of the critical point. The effect is attributed to proximity superconductivity in GaAs resulting from the use of superconducting point contacts.

The invasive role of probes in the measurement process is a well-known feature of modern physics. However, the specific role of contacts in standard transport studies remains unclear because of the difficulties involved in separating the intrinsic properties of the host system from the changes induced by the presence of contacts. Heterointerface junction contacts between superconductors and semiconductors may be used to gain additional insight into this problem since the transport characteristics of semiconductors and the temperature variation in the properties of the superconductor are relatively well understood. In such systems, the change in transport characteristics of the semiconductor induced by the onset of contact superconductivity, for relatively small temperature changes in the vicinity of T_c of the superconductor, should be separable from the slowly varying, intrinsic characteristics of the semiconductor. This would provide an indication of the relative influence of contacts upon the measured properties. In addition, the problem also has technological significance since the superconductor-semiconductor interface (contact) may be used to endow semiconductors with the much-desired properties of superconductors, via the proximity effect, in order to realize a high-speed, low-dissipation, three-terminal superconducting transistor.[1]

Here, we identify a magnetoresistance anomaly in the measured transport properties of bulk GaAs that originates from the use of superconducting In point contacts (probes). The anomalous part of the magnetoresistance which is observed below a critical temperature, $T_c = 3.4$ K, is shown to be described by a homogeneous function of B and T of the form $[\Delta R(T,B)/R]_s = A\tau^\kappa f(B/\tau^\beta)$ with $\kappa = 1.00 \pm 0.25$, $\beta = 1.00 \pm 0.33$, and $\tau = (T_c - T)/T_c$.[2] There is concurrence between this observed law of corresponding states and the BCS prediction for the temperature variation of the critical magnetic field needed to quench superconductivity near T_c, and also agreement between T_c for the onset of the resistance correction and the superconducting transition temperature for the In contacts. These two facts point to the enhanced reflection of current-carrying electrons, by a proximity-effect-induced gap in the single-particle density of states below the superconducting point contacts, as the possible mechanism for the resistance correction. Our results provide insight into the nature of the semiconductor-superconductor interface in GaAs and they also suggest a nontrivial invasive role for superconducting point contacts in conventional electrical measurements.

Transport measurements were carried out on a series of Si- (Sn-) doped GaAs epilayers, 0.3–1.0 μm thick, prepared by molecular beam epitaxy (MBE) [metal-organic chemical-vapor deposition (MOCVD)]. Rectangular bars up to 2 mm$\times$1 cm were cleaved from large-area wafers, and <0.5-mm-dia. In contacts were alloyed for 90 sec at 380°C, along the edges of the sample in a Hall configuration. The four-terminal transverse ($I \perp B$) magnetoresistance and the Hall effect were measured with the samples immersed in pumped liquid helium, and field sweeps of the data were collected with a computer. The Hall effect indicated that the free-carrier density n in these samples spanned the range $3\times10^{18} < n < 1.5\times10^{19}$ cm^{-3} and n showed little variation $<10\%$ between $4.2 < T < 300$ K.

Figure 1 shows $\Delta R/R$ versus B for a 1.0-μm thick, Si-doped, $n = 5\times10^{18}$ cm^{-3}, GaAs sample (sample 1). Here, the magnetoresistance data have been symmetrized about $B = 0$ in order to eliminate admixtures of the Hall effect resulting from contact misalignments, and the data have been plotted as $\Delta R/R$ versus B in order to highlight frac-

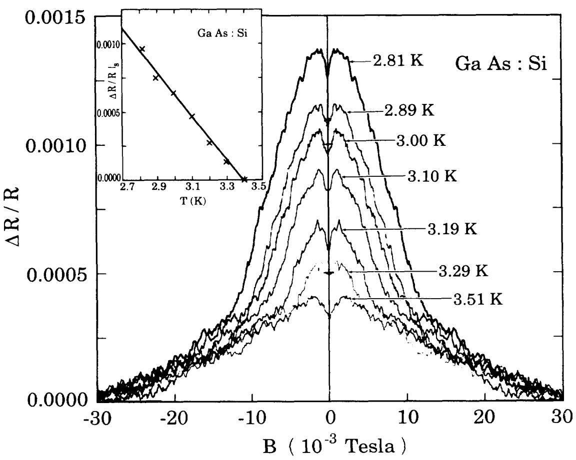

FIG. 1. The fractional variation of the resistance, $\Delta R/R$, is plotted vs B for sample 1. The inset shows the variation of R, measured with respect to the 3.51-K curve at $B=0$, i.e., $(\Delta R/R)_s$, vs T.

tional changes of the magnetoresistance in the vicinity of $B=0$. In addition, a nonstandard definition $\Delta R/R=[R(B)-R(B_N)]/R(B_N)$, where $B_N=30$ mT, has been adopted in order to preserve the form of the T dependence of the raw data. Consider the data curve for 3.51 K, which shows positive magnetoresistance for $B<2$ mT followed by negative magnetoresistance to $B=30$ mT. The magnitude of this *background magnetoresistance* correction is $(\Delta R/R)_B=3\times10^{-4}$ to $B=30$ mT. Further study of this sample for $T>4.2$ K revealed that the weak positive magnetoresistance observed in the vicinity of $B=0$ decays with increasing T and vanishes for $T>10$ K while the negative magnetoresistance persists to higher T. These features and the field dependence of the negative magnetoresistance suggest that the background originates from weak localization; the weak positive magnetoresistance in the vicinity of $B=0$ reflects strong spin-orbit scattering.[3,4]

A reduction in T below 3.51 K (see Fig. 1) shows the abrupt onset of an anomalous, additional contribution to $\Delta R/R$ that appears superimposed upon the background magnetoresistance (see Fig. 1). The magnitude of $\Delta R/R$ at $B=0$, when measured relative to the background, increases linearly with decreasing tempertures below a critical temperature T_c (see inset, Fig. 1), and a linear fit to the data indicates that $T_c=3.4$ K. The full width at half maximum (FWHM), ΔB, of the anomalous magnetoresistance term also grows larger with decreasing temperatures below T_c (see Fig. 1), but *the overall shape of the signal does not change with* T for $T<T_c$. The temperature and magnetic-field dependence of the resistance anomaly, $(\Delta R/R)_s$, may be better studied by subtracting the background magnetoresistance, $(\Delta R/R)_B$, from the net measured magnetoresistance correction $\Delta R/R$, i.e., $(\Delta R/R)_s=\Delta R/R-(\Delta R/R)_B$. As $(\Delta R/R)_B$ was found to be relatively insensitive to T up to 10 K, any data curve in the range $3.4<T<10$ K could have been used for background subtraction. Here, we choose the 3.51-K data for $(\Delta R/R)_B$. The invariance of the shape of the resistance anomaly with T below T_c suggests that $(\Delta R/R)_s$ may be described by a simple function, $(\Delta R/R)_s=F(T,B)$, which exhibits some elegant properties under scale change below T_c. In order to point out these properties, we define a reduced temperature, $\tau=(T_c-T)/T_c$, and consider the data of Fig. 1 for $\tau>0$ $(T<T_c)$. Then, given the resistance correction $F(\tau,B)$, the correction for a different set of arguments, i.e., $F(\tau'=\lambda\tau,B'=\lambda B)$, appears to obey the relation $F(\lambda\tau,\lambda B)=\lambda F(\tau,B)$, which is characteristic of a first-order homogeneous function of two variables, i.e., $F(\tau,B)=\tau F(1,B/\tau)$ if $\lambda=\tau^{-1}$. Let $F(1,B/\tau)=A_0 f(B/\tau)$, where A_0 is a sample-dependent constant. Then, the argument of the scaling function f, which describes $(\Delta R/R)_s$, is a single variable, the scaled combination B/τ.[2] The simple behavior suggested by the above arguments may be tested by replotting the data of Fig. 1 in terms of the natural variables, i.e., $(\Delta R/R)_s/\tau$ versus B/τ, of the problem. Figure 2 shows a replot of the data of Fig. 1 in terms of these variables; the figure demonstrates data collapse and confirms the proposed law of corresponding states. The data of Fig. 1 have also been examined under the assumption that the resistance correction is a generalized homogeneous function of its arguments, i.e., $F(\tau,B)=A_0\tau^{\kappa}f(B/\tau^{\beta})$ with $\kappa,\beta\neq1$. These studies indicate that the exponents $\kappa=1.00\pm0.33$ and $\beta=1.00\pm0.25$.

A total of nine similarly prepared samples with In contacts were studied in order to confirm reproducibility of the effect and all samples exhibited the resistance anomaly below 3.4 K. As an example, Fig. 3 shows $\Delta R/R$ versus B for a second Si-doped GaAs sample (sample 2), $n=1\times10^{19}$ cm^{-3}, with superconducting (In) point contacts. Note the absence of the high-temperature background observed in the data of Fig. 1. However, the anomalous resistance correction appears abruptly when T is reduced below 3.5 K, i.e., $T_c=3.4$ K, and its magnitude and FWHM increase linearly with decreasing T as in the data of Fig. 1. Scaling of the magnetoresistance anomaly was confirmed by data collapse when the data were replotted as $(\Delta R/R)_s/\tau^{\kappa}$ versus B/τ^{β}, and the mea-

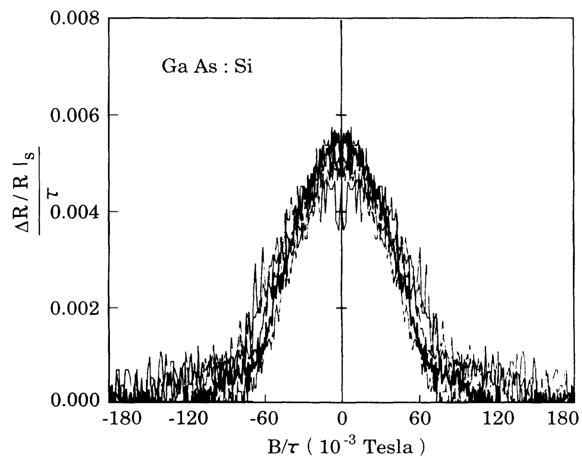

FIG. 2. The data of Fig. 1 are replotted in terms of the natural variables, i.e., $(\Delta R/R)_s/\tau$ vs B/τ, to demonstrate scaling.

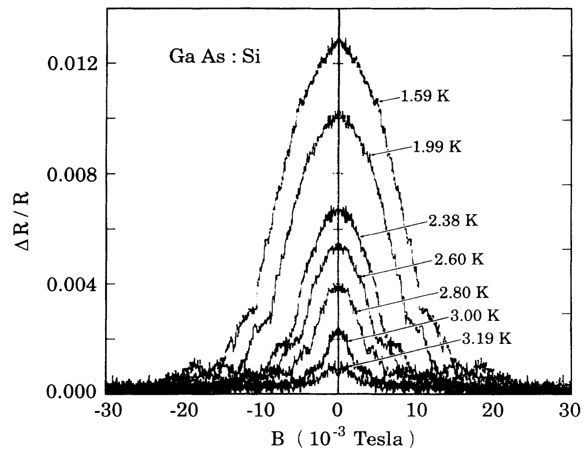

FIG. 3. The fractional variation of the magnetoresistance, $\Delta R/R$, is plotted vs B for sample 2.

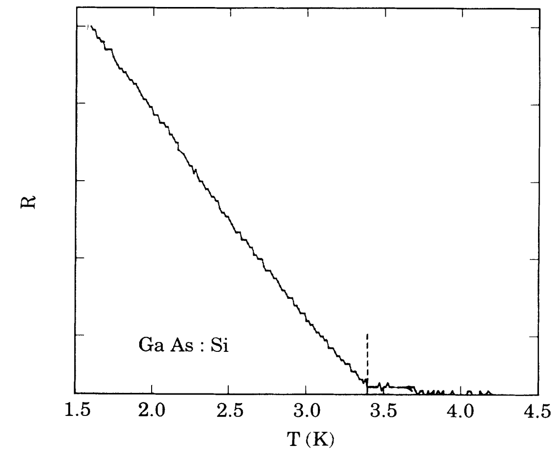

FIG. 4. The four terminal resistance R is plotted vs T for $B=0$. The discontinuity in the slope, dR/dT, at $T=3.4$ K reflects the superconducting transition in the contacts.

sured exponents, $\kappa=1$ and $\beta=1$, agreed with the results for sample A. The abrupt onset of the anomalous resistance correction below T_c is indicative of a phase transition at $T=T_c$ which has been directly observed in the T dependence of $R(B=0)$ (see Fig. 4). Figure 4 shows a temperature-independent resistance at high temperatures, $T>3.5$ K, which is followed at lower temperatures by a linear variation of R versus T. The linear variation of R for $T<T_c$, which is due to the anomalous resistance correction shown in Figs. 1 and 3, follows a discontinuity in the temperature coefficient of the resistance dR/dT at $T=T_c$. Thus, we argue that the anomalous magnetoresistance *reflects* an order parameter that characterizes a second-order phase transition.

Although the experimental data do not allow for a direct determination of the origin of the effect, we point out that a strong magnetic field quenches the anomalous magnetoresistance term and, hence, the order parameter for $T<T_c$. We note several additional compelling features in the data that indicate that the order parameter reflected in our studies is the wave function Ψ for the superconducting state, i.e., the degree of superconducting order in the vicinity of the superconducting point contacts.[5] First, the critical temperature for the onset of the anomalous magnetoresistance in our studies, $T_c=3.4$ K, shows good agreement with the superconducting transition temperature of In, 3.4 K.[6] Second, T_c could be monotonically reduced with the application of hydrostatic pressure to 7 kbars and dT_c/dP was found to be consistent with expections for In.[7] Third, transport studies of samples from the same wafer with nonsuperconducting Au-Ge/Ni contacts have failed thus far to show a similar scaling correction to the resistance. Finally, the combination of B and τ that is the argument in our law of corresponding states is also consistent with superconductivity. The T dependence of the critical field $B_c(T)$ for an ideal, type-I superconductor is given by the empirical parabolic relation $B_c(T)/B_c(0)=(1-T^2/T_c^2)$,[6] which may be reexpressed in terms of τ as $B_c(T)/B_c(0)=2\tau-\tau^2$. Although superconductivity in GaAs due to the proximity effect may be expected to show deviations from the expected behavior for bulk superconductors, the scaling variable should follow the expectations for bulk superconductivity in the vicinity of the critical point; i.e., for sufficiently small τ, the argument of the scaling function is expected to be B/τ.

In order to understand why the resistance of a macroscopic sample [see Fig. 5(a)] reflects the onset of superconductivity in the vicinity of the contacts, we present a possible picture for the formation of alloyed contacts on GaAs.[8,9] Typically, etched In dots are placed upon the native oxide layer (10–50 A thick) that covers the GaAs surface and is heated ($\simeq$380 °C) such that the In dots melt and break through the oxide layer. Then, molten In dissolves GaAs (melting point $\simeq$1500 K) and a heavily In-doped GaAs layer is regrown epitaxially beneath the In dots as the sample is cooled. As In is a group-III element, substitution of Ga with In is not expected to dope the material. However, the formation of $In_xGa_{1-x}As$ reduces the band gap and the Schottky barrier near the surface, which makes possible the equilibration of the electrochemical potential of the contact μ_c and the electrically active region of the sample in the vicinity of the contact via tunneling through the reduced Schottky barrier [see Fig. 5(c)].[9] The narrow Schottky-barrier width, $d(10^{19}\ \mathrm{cm}^{-3})\simeq 10^{-8}$ m, in these heavily doped samples, and the intimate electrical contact between the current-voltage probes and the semiconductor, possibly allows Cooper pairs from the In voltage probes to tunnel across the Schottky barrier and penetrate into the GaAs over length scales of order $\lambda\simeq 10^{-7}$ m, sufficient to interfere with the current flow in these samples [see Fig. 5(b)].[10–13] As transport at weak magnetic field proceeds by electrons scattering from state to state in the vicinity of the Fermi level, a gap in the electronic density of states of the GaAs near the superconductor-semiconductor interface, induced by the proximity effect,[11] prohibits single electron flow beneath the voltage probes on the semiconductor as qualitatively illustrated in Fig. 5(b) i.e., the (proximity) superconducting regions beneath the voltage probes act as macroscopic barriers to the current flow in our GaAs samples. Then, the incident current is redirected below

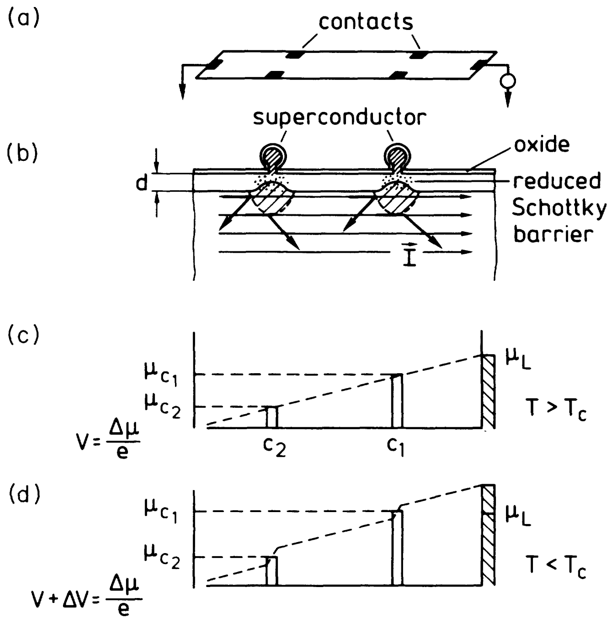

FIG. 5. (a) A sample in the Hall geometry. (b) Cross section of semiconductor showing a Schottky barrier of width d, between an oxide-covered semiconductor surface and the current I, carrying sample interior. Cross-hatched areas correspond to superconducting regions. (c) The electrochemical potential of a metal contact, μ_c, equilibrates with the local, average sample value and the measured voltage drop is $\Delta\mu/e$. (d) The measured voltage drop, for fixed I, is enhanced by proximity superconductivity in GaAs. The additional voltage drop corresponds to additional reflection due to a single contact.

these regions as the proximity effect "pinches off" conduction near the surface, and the resulting enhanced current density in the GaAs directly below the contacts increases the measured voltaged drop between the voltage probes, as illustrated in Fig. 5(d). Here we have assumed that the voltage probes equilibrate at an equipotential value that is the average of the potential drop across the contact. The magnitude of the resistance correction $(\Delta R/R)_s$ is expected to be a complicated function of $\lambda(T)$, the induced gap that deceases monotonically away from the semiconductor-superconductor interface, and possible over-the-gap tunneling in the proximity region. Thus, we provide an estimate for $(\Delta R/R)_s$ from the estimated effective cross-sectional area excluded for current flow in the semiconductor, $(\Delta R/R)_s \simeq \lambda w/A \simeq 0.01$. Here, w, is the effective width of the contact and A is the cross-sectional area for current flow in the semiconductor. Incident electrons that penetrate the superconducting regions can, in principle, produce supercurrent flow in the GaAs at the semiconductor-superconductor interface. However, it is necessary to convert incident single electrons to Cooper pairs via Andreev reflection of a hole at the boundary between the (proximity) superconducting and semiconducting regions.[14] One would expect this pair-conversion process to be suppressed since it is of second order in the transmission coefficient for a single electron across the semiconductor-superconductor boundary.[12] As we observe an enhancement in the electrical resistance below T_c, we suggest that the experimental results are consistent with these expectations.

In summary, we have observed a magnetoresistance anomaly in bulk GaAs, $\Delta R/R \sim 10^{-3}$, which occurs only below a critical temperature T_c when superconducting point contacts are used as the current and voltage probes. The resistance correction shows scaling as: $[\Delta R(T,B)/R]_s = A_0\tau^{\kappa}f(B/\tau^{\beta})$, where $\tau=(T_c-T)/T_c$, $\kappa=1.00\pm0.25$, and $\beta=1.00\pm0.33$. These electrical properties suggest a nontrivial, invasive role for superconducting contacts in conventional four-probe electrical measurements, and they also provide a demonstration of scaling of electronic transport in a semiconductor system.

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