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Andreev reflections at interfaces between $\delta$-doped GaAs and superconducting Al films

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By placing several Si $\delta$-doped layers close to the surface of a GaAs molecular beam epitaxy–grown crystal, we achieve a compensation of the Schottky barrier and obtain a good Ohmic contact between an in situ deposited (without breaking the vacuum) Al metallization layer and a highly modulation doped ($n^+$) conduction layer embedded below the $\delta$-doped layers in the GaAs crystal.

The key parameter in the description of Andreev reflections is the dimensionless parameter $Z$, which enters the expression for the normal resistance of a N–S interface $R_N = R_0 (1 + Z^2)$. $R_0$ is the barrierless resistance, whereas $Z$ is a measure of the effective interface barrier height. In a model system with a $\delta$-function barrier $Z$ is given by $Z = \sqrt{Z_0 + (1 - r)^2} / 4 r$, where $Z_0 = H / \hbar v_F^{\text{nm}}$ and $r = v_F^{\text{nm}} / v_F^{\text{sp}}$. Here $H$ is the strength of the $\delta$-function barrier and $v_F^{\text{nm}}$, $v_F^{\text{sp}}$ are the Fermi velocities in the normal metal and the superconductor, respectively. The contributions to $Z$, thus, come from an interface energy barrier and a Fermi velocity mismatch between the two materials. The lower the $Z$ the higher is the probability for Andreev reflection processes at the S–N or S–Sm interfaces. Another important quantity is the coherence length in the normal metal (or degenerated semiconductor). This length determines the length scale over which electrons and Andreev reflected holes can maintain their phase coherence. In the dirty limit where the electronic mean free path $l$ is much shorter than the coherence length, $\xi = \sqrt{h D / 2 \pi k_B T}$, where $D = \frac{1}{2} v_F^{\text{nm}} l$ is the diffusion constant for diffusion in three-dimensions.

The above definitions of the important quantities draw the attention to the choice of materials. III–V semiconductors have played a key role, with highly doped InAs as the preferred material due to its ability to form very low interface barriers with most metals deposited on the surface. $p$-type InAs forms a two-dimensional (2D) electron gas inversion layer at the surface but, unfortunately, with a rather low mobility. More advanced materials such as InAs–AlSb quantum wells were used by Nguyen et al. Here a planar structure with a 2D carrier density of roughly $10^{12}$ cm$^{-2}$ and mobilities of the order of $10^4$ cm$^2$/Vs (corresponding to mean free paths of 1.3 $\mu$m) was successfully used to obtain S–Sm–S structures exhibiting well pronounced supercurrent. Kleinasser et al. have employed backgated $n$-type In$_{0.47}$Ga$_{0.53}$As grown on $p$-type InP substrates to produce three-terminal Josephson field effect transistor devices. In both these works a clear excess current was observed, indicating $Z$ factors around 1 or below. Another approach is the use of annealed Ti/Sn contacts to a GaAs/AlGaAs heterostructure containing a 2D electron gas buried below the surface.

All the above works, however, rely on rather involved processing procedures. To obtain a high interface transmissivity and a long coherence length, one needs a high doping level and a high carrier mobility in the semiconductor channel. These two demands are not easily combined, and one often has to choose a suitable compromise. In this Letter we report a new and very simple method for making planar S–Sm–S structures with very high contact transmissivities and reasonably long coherence lengths. From a technological point of view GaAs is the most studied among the III–V materials, and many experimental groups have access to molecular beam epitaxy (MBE) systems with Ga, As, Al, and Si sources.

Our samples consisted of 200 nm GaAs grown in a MBE chamber on an undoped GaAs substrate. The 200 nm were doped with Si to $4.4 \times 10^{18}$ cm$^{-3}$ and capped with 5

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\[ \delta \text{-doped layers separated by } 25 \text{ Å of undoped GaAs. Each of the } \delta \text{-doped layers contained } 5 \times 10^{13} \text{ cm}^{-2} \text{ Si atoms. These layers were inserted to decrease the Schottky barrier at the subsequent Sm–S interface formed as the structure was terminated with 200 nm of pure Al, which was deposited after the substrate temperature had fallen to about } 30 \text{ °C} \text{ to prevent the formation of AlAs at the interface. As seen in Fig. 1, the insertion of the } \delta \text{-doped layers had a dramatic effect on the interface resistance. The contact resistivity was lowered by three orders of magnitude from about } 10^3 \text{ to about } 0.5 \times 10^{-10} \text{ Ω m}^2 \text{. A } 17 \text{ μm wide mesa structure was etched in the Al and the doped GaAs layer, and Ti/Au bonding pads were deposited. A } 1 \text{ μm wide line was then etched in the Al across the mesa using conventional electron beam lithography with poly(methylmethacrylate) resist. The Al was wet-etched in } H_2 PO_4 :H_2 O (1:2) \text{ at } 50 \text{ °C for about } 2 \text{ min. The two-terminal resistance was dominated by the oxide barriers between the Al and the Ti/Au pads, whereas the four-terminal resistance exclusively probed the } 1 \text{ μm long Al–GaAs–Al configuration. In order to make a systematic study of the electrical properties of the S–Sm–S interface, the line across the } 17 \text{ μm wide mesa was etched in meander patterns of different total lengths as exemplified in the inset of Fig. 3. The mobility of the doped GaAs layer with the Al removed from the surface was } 0.132 \text{ m}^2/\text{V s and the carrier density } 4.75 \times 10^{11} \text{ m}^{-3}. \text{ This gave a mean free path of roughly } 50 \text{ nm and a } 0.3 \text{ K coherence length of } 250 \text{ nm. The lowest obtainable } Z \text{ factor for } H = 0, \text{ i.e., assuming solely a contribution from the Fermi velocity mismatch between the } \delta \text{-doped GaAs layer and the Al, would be } 0.39. \text{ From our experiments we deduced } Z \text{ values in the range } 0.7–0.9 \text{ for the } \delta \text{-doped samples.}

\text{The critical temperature for our Al films was about } 1.2 \text{ K, and the electrical measurements were performed in a } ^3\text{H cryostat with a base temperature of } 0.3 \text{ K. In our experimental setup, we applied a dc voltage bias and superimposed a small sinusoidal ac modulation, that allowed us to measure the differential resistance and the } I–V \text{ characteristics simultaneously. The ac bias was kept sufficiently low to ensure that the measured ac voltage remained much lower than } k_B T/e. \text{ Above } T_c, \text{ the } I–V \text{ characteristics were linear. Below } T_c, \text{ the characteristics became nonlinear. At very high biases the differential resistance reached the normal resistance level } R_N. \text{ An excess current relative to the normal state characteristic was detected until a certain voltage } V_e, \text{ where Joule heating caused a breakdown of superconductivity in the banks near the normal conductor. This breakdown resulted in an abrupt jump of the current from the excess current in the superconducting state to the normal state current. This jump gave rise to a sharp peak in the differential resistance. As seen in Fig. 1(b), samples cut from a wafer without } \delta \text{ doping exhibited a deficit current. Above } V_e, \text{ irregularities or mesoscopic fingerprints were detected in the differential resistance on top of a constant level equal to the normal state resistance } R_N. \text{ The peak heights at } \pm V_e \text{ and the mesoscopic fingerprints above } V_e \text{ and below } V_e \text{ were not always fully symmetric. Below } V_e, \text{ the differential resistance dropped to an overall level lower than } R_N. \text{ This lower resistance level we denote } R_S. V_e \text{ is not the gap voltage } 2 \Delta/e \text{ since it had different values for samples with different shape of the }}\]
Vc was observed. As seen in Fig. 2, the fine structure below symmetric around zero bias voltage. The precise shape of boundary conditions and solutions above are solved in the normal state with suitable where

\[ \chi(x) = \frac{\rho_{sm}/\rho_n}{I_{SW}} + R_{sm}, \]

(3)

where \( R_{sm} = \rho_{sm}L/dw \) is the resistance of the piece of semiconductor of length \( L \) between the superconducting banks, while \( \rho_n \) is the normal state contact resistivity with dimension [\( \Omega \) m²]. \( I_S = \sqrt{\frac{\rho_{sm}}{\rho_n}} \) is the decay length for \( V(x) \) across each of the S–Sm interfaces away from the etched stripe. For samples cut from the δ-doped wafer \( I_s \) was of the order of 0.5 \( \mu m \), while for solely modulation doped samples it was roughly 60 \( \mu m \). In the superconducting state, the energy gap will, thus, appear at voltages \( V_{appl} = 2 \Delta/e + R_{sm}I \).

In Fig. 3 we show the \( dH/dV \) and \( I-V \) curves for a typical sample. In Fig. 3 we have indicated the positions of \( \pm 2\Delta/e, \pm \Delta/e, \) and \( \pm 2\Delta/3e \). We interpret the observed structure as subharmonic energy gap structure originating from multiple Andreev scattering across the S–Sm–S junction.\(^9\) This structure can persist even to \( T = 0 \) with unaltered amplitude. The value of \( \Delta \) is, however, subject to a voltage dependence due to the self-heating effect. The dip at zero bias was not present in all our samples and is, presumably, a precursor to a supercurrent, or the so-called zero bias excess conductance observed by many workers.\(^10\)

In conclusion, we have demonstrated a new and very simple technique to make S–Sm–S structures with high interface transmissivities. In our samples we have observed high bias excess current and subharmonic energy gap structure. Finally, we have demonstrated how to interpret data taken in a planar geometry.

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