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Superconducting Junctions of InAs Semiconductor Nanowires

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Abstract

InAs semiconductor nanowires can provide a promising platform to integrate superconducting quantum circuit, which exploits tunable supercurrent under the operation of gate voltage. We report temperature and magnetic field dependence of the nanowire superconducting junctions, which is in agreement with the proximity-effect theory of superconductor-normal metal-superconductor weak link. Superconducting coherence length of the InAs nanowire is estimated from the fit and magnetic-field dependence of the critical current and the subgap structure of dI/dV is discussed as well.

Keywords : semiconductor nanowire, proximity effect, Andreev reflection

I. Introduction

In recent years semiconductor nanowires (NWs) have drawn a lot of attentions for their huge potential applications for nanoelectronics and nanophotonics [1]. Highly controlled synthesis of single-component and heterostructure NWs has also provided a new platform to study various quantum phenomena in low dimensional system at low temperature [2], which is promising for novel quantum devices. Furthermore, contacted with conventional superconductors, semiconductor NW's have been used to realize Josephson field-effect transistors [3] and gate-tunable superconducting quantum interference devices [4] at the nanoscale. Huge versatility in composition of nanowires and relatively simple fabrication process would enable the integration of superconducting quantum circuits for the applications in quantum information technology.

InAs NW can be a good material system to fabricate a superconducting nano-junction, since it forms a highly transparent contact with a conventional superconductor [3]. The critical current I_c of the supercurrent is a basic parameter to characterize the superconducting junction. However, its temperature- and magnetic-field-dependent behavior has not been well studied yet. Here we report an extensive study of I_c with respect to the temperature and external magnetic field, from which we can estimate the superconducting coherence length ξ_N to be about 210 nm at T = 40 mK. Characterizing basic properties of the NW superconducting junctions would be useful to design

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and integrate superconducting quantum circuit.

II. Experiments

Single crystalline InAs NW's are grown on a Si substrate via the vapor-liquid-solid process technique with laser ablation method. Au nano-particles are used as catalysts. After the growth, NW's are dispersed in chlorobenzene solution and deposited on a p^+ Si substrate with a 250-nm-thick SiO_2 overlayer. Electron-beam lithography is used to define electrode patterns and thin film of Ti(5 nm)/Al(120 nm) is deposited using electron-beam evaporator. The NW surface is treated with oxygen plasma and buffered hydrofluoric acid to remove residual layer of the electron-beam resist and surface oxide layer. A representative individual nanowire device is shown in the inset of Fig. 1.

Low-temperature electronic transport of each device has been measured in a dilution cryogenic system with low-noise filtered electronics. To reduce the external noise effects, the measurement leads were filtered by π filters at room temperature and by low-pass RC and copper powder filters at the temperature of the mixing chamber in a dilution refrigerator.

III. Results and Discussion

Fig. 1 shows a typical hysteretic behavior of the current-voltage (*I*-*V*) characteristics of the InAs NW superconducting junction for device **D1** at $T = 40$ mK, which is far below the superconducting transition temperature, T_c, of 1.1 K. The NW junction shows a clear supercurrent branch up to $I \sim 100$ nA and a dissipative one as well, as shown in the figure. The hysteretic behavior, which is a typical feature of capacitively shunted Josephson junction [5], is presumably due to a capacitance between the source-drain electrodes and the conductive Si substrate.

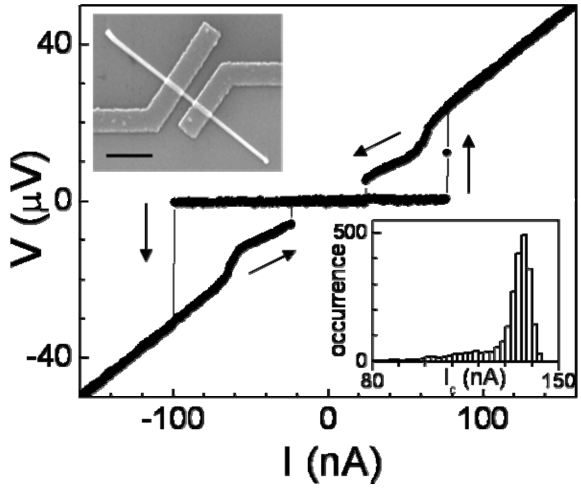

Fig. 1. Current-voltage (*I*-*V*) characteristics of device **D1** at $T = 40$ mK. Supercurrent branch is observed up to $|I| \sim 100$ nA. Arrows indicate a hysteresis with respect to a sweeping direction of bias current. For **D1** the InAs NW has a diameter $\phi = 130$ nm and the inter-distance between two superconducting electrodes is $L = 170$ nm. Upper inset: scanning electron micrograph of a representative nanowire device. Scale bar is for 1 μm. Lower inset: statistical distribution of I_c after 2400 measurements. The occurrence shows a peak at $I_c = 137 \pm 1$ nA.

Since the switching current from the supercurrent branch to the dissipative one fluctuates around the critical current, a statistical distribution of the switching current is obtained to determine I_c. A low-frequency (20 Hz) sinusoidal current was applied to the NW junction and the switching current was recorded when the corresponding voltage jump exceeded a threshold value of $V_{th} = 6$ μV. Resulting distribution of the switching current out of 2400 measurement points is shown in the lower inset of Fig. 1 with an occurrence peak at $I_c = 137 \pm 4$ nA.

Temperature dependence of I_c is displayed in Fig. 2(a) for different two devices. The normal-state resistance R_N, which is defined to be a dynamic resistance dV/dI value at $V = 0.5$ mV, is constant in our experimental range of temperature. According to the proximity-effect theory [6] of superconductor-normal metal-superconductor (SNS) weak link, temperature dependence of the critical current is given to be $I_c(T) \sim \exp(-L/\xi_N(T))$ where L is the source-drain spacing and $\xi_N(T) = \xi_N(T_c)(T_c/T)^{1/2}$ is the

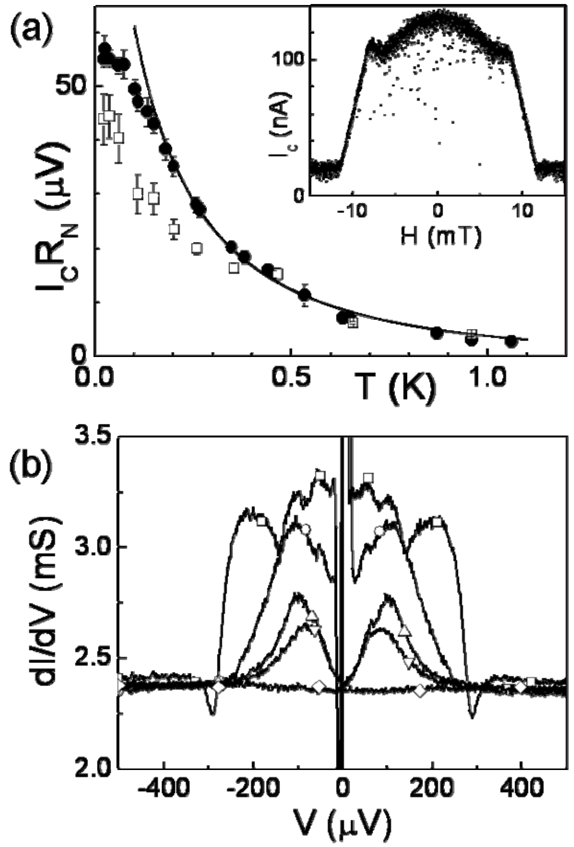

Fig. 2. (a) Temperature dependence of I_cR_N product for device **D1** (circle) and **D2** (square) with R_N = 420 and 680 Ω, respectively. Solid line is a fit to a proximity-effect theory, which is explained in the text, for **D1**. For **D2** the NW diameter is ϕ = 80 nm and the electrode spacing L = 110 nm. Inset: Magnetic-field H dependence of I_c for **D1**. H is applied in a direction perpendicular to the substrate. (b) H-dependent differential conductance dI/dV for **D1** with H = 0 (square), 10 (circle), 20 (up triangle), 30 (down triangle), and 50 (diamond) mT, respectively, from top to bottom.

superconducting coherence length in the normal metal in the dirty limit. From a fit to the theory we obtain $\xi_N(T_c)$ = 38 ±1 nm, which results in ξ_N = 200 ± 4 nm at T = 40 mK, for **D1**.

Magnetic-field dependence of I_c is shown in the inset of Fig. 2(a) at T = 40 mK with respect to the magnetic field, H, applied perpendicular to the substrate. Scattered data are caused by a fluctuation of the switching current. Up to H = 6 mT, gradual suppression of I_c resembles a typical feature of I_c modulation induced by H, which is so-called a "Fraunhoffer pattern" [5]. Above H = 8 mT, however, rapid suppression of I_c is observed as the superconductivity of the electrode is broken by the external magnetic field. From a linear extrapolation of the I_c data near the transition region, we can estimate the critical magnetic field, H_c, of the superconducting Al electrode to be H_c = 12 mT. Another three more devices show similar behavior (not shown here).

With the application of H, progressive change of dynamic conductance dI/dV is shown in Fig. 2(b) as a function of V. For H = 0 mT, the overshoot near V = 0 indicates the existence of the supercurrent, while the overall conductance enhancement below $V \sim 300$ μV is caused by Andreev reflection [7]. Specifically, a series of dI/dV peaks at $V = 2\Delta/me$, where 2Δ = 210 μeV is a superconducting gap energy and m = 1, 2, 3, is attributed to multiple Andreev reflection [8]. As we increase H, I_c is suppressed to be zero at H = 20 mT, which is consistent with the observation in the inset of Fig. 2(a). It should be noted that the superconducting gap feature is robust to be observed even with the absence of the supercurrent for $H < 50$ mT. Thus it is crucial to nullify the external magnetic field to maximize the proximity-induced superconductivity of the semiconductor NW's.

IV. Conclusion

We have fabricated superconducting junctions of InAs NW's using Al as a superconducting electrode. Temperature dependence of the critical current I_c is in good agreement with the proximity-effect theory of the SNS weak links. Superconducting coherence length of InAs nanowire is estimated to be ~ 200 nm at T = 40 mK. Magnetic-field induced modulation of the critical current was not complete, limited by the small value of the critical field H_c. Quantitative information of the basic junction parameters would be useful to design superconducting quantum circuit based on the InAs NW's.

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