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Laterally proximized aluminum tunnel junctions

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This letter presents experiments on junctions fabricated by a technique that enables the use of high-quality aluminum oxide tunnel barriers with normal metal electrodes at low temperatures. Inverse proximity effect is applied to diminish the superconductivity of an aluminum dot through a clean lateral connection to a normal metal electrode. To demonstrate the effectiveness of this method, fully normal-state single electron transistors (SETS) and normal-metal-insulator-superconductor (NIS) junctions applying proximized Al junctions were fabricated. The transport characteristics of the junctions were similar to those obtained from standard theoretical models of regular SETs and NIS junctions. © 2011 American Institute of Physics. [doi:10.1063/1.3590922]

An important element in nanoelectronic circuits is a tunnel barrier between two leads, with applications ranging from superconducting qubits and quantum metrology devices to electronic refrigeration by hybrid normal metal-insulator-superconductor (NIS) junctions. A standard material for yielding high-quality junctions is aluminum due to rapid oxidation of its surface into a thin and stable layer of insulating aluminum oxide (AlOx) under oxygen exposure. Aluminum is superconducting below the critical temperature Tc = 1.2 K in bulk and up to 2.7 K in thin films. High-quality nanoscale junctions are typically fabricated in a single vacuum cycle by shadow evaporation of metals at multiple angles through a suspended mask, combined with in situ oxidation. Depositing a layer of normal or superconducting material on top of oxidized Al forms a NIS or a superconductor-insulator-superconductor (SIS) junction.

Regrettably, fabrication of low temperature normal metal-insulator-normal metal (NIN) junctions or NIS junctions with non-Al superconductor is not straightforward. The latter would be beneficial in terms of controlling the Tc through the choice of material: a higher Tc would benefit for example a current standard based on the hybrid SINIS tunnelist while a lower Tc would be efficient for low temperature NIS coolers, where the optimal cooling power is at T = 0.45Tc. In order to use Al for either NIN junctions or NIS junctions with non-Al superconductor, its superconductivity must be suppressed. Alternatively, aluminum can be isotropically deposited as a thin layer on top of the N electrode, after which it is thoroughly oxidized before depositing the counterelectrode. When applied with shadow evaporation the latter technique, however, requires caution to ensure uniform Al coverage to avoid short circuits.

The aluminum superconductivity may be suppressed by various means, such as by applying a magnetic field. However, magnetic fields are not always desirable when combining NIN and NIS junctions on a single circuit, for example, when combining normal-state single electron transistors (SETS) with NIS thermometers and coolers. Although it is possible to have both NIN and NIS Al-based junctions in a single circuit by controlling the thicknesses and thus the critical fields of Al layers, in some applications external fields cannot be tolerated. Another approach is to dope Al with, e.g., manganese impurities to control or diminish the Tc while retaining the BCS density of states, but the junction quality could be compromised, and it is undesirable to have both manganese-doped and pure superconducting materials in the same evaporator due to the risk of contamination. Also the use of inverse proximity effect arising in a normal metal-superconductor (NS) bilayer is a widely used technique for modifying the superconductor Tc: the normal metal gains a superconducting character while the superconductor gains normal metal features at a short distance from the interface.

This letter introduces a technique for suppressing the Al superconductivity in small tunnel junctions by utilizing the inverse proximity effect in lateral direction. According to the theory of diffusive, inhomogeneous proximity superconductivity, the superconductivity is fully suppressed in a NSN structure with infinite-size N reservoirs, when the length of the quasi-one-dimensional S-material wire L < πξ0. By symmetry, for a NS structure the suppression is achieved for L < πξ0/2. Utilizing our fabrication process the Al film superconducting coherence length is typically ξ0 = 100 nm, yielding L = 150 nm. When taking into account the nonideal interface, a short Al wire with L ~ 100 nm, proximized by a long normal metal lead, forms a high-quality NIN or NIS tunnel junction.

The proximized Al junctions were utilized in the fabrication of several normal-state SET samples with multilayer shadow evaporation, for which the mask layout is shown in Fig. 1(b). Figure 1(a) sketches a cross-section of a proximized Al junction that is used in the sample. The samples were fabricated onto an oxidized silicon substrate covered by a resist mask consisting of 500 nm thick copolymer layer at bottom and 50~70 nm thick polymethyl methacrylate layer on top, patterned by electron beam lithography. The fabrication process had the following order, illustrated in Fig. 1(a): first a 15 nm layer of aluminum at the angle θ=0° is evaporated to form two small Al dots 400 nm apart, directly followed by a thick (45 nm) layer of copper at θ=30° to partially cover the dot with a proximizing normal metal lead. Third, the remaining uncovered aluminum is oxidized in the evaporation chamber, after which the SET is formed by depositing a 30 nm copper layer at θ=−30° to contact the two Al dots.

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The suppression of the Al dot superconductivity was examined by measuring the current $I_{\text{SET}}$ as a function of applied bias and gate voltages, $V_{\text{bias}}$ and $V_g$, respectively, according to the circuit diagram in Fig. 1(c). The samples were measured in a $^3$He-$^4$He dilution refrigerator with a base temperature close to 40 mK. The results for the SET of Fig. 1(c) with highest charging energy $E_C=525$ μeV are shown in Fig. 2. All of the measured structures showed similar behavior. Figures 2(a) and 2(b) show the range over which $I_{\text{SET}}$ varies as $V_g$ is swept, fit by a standard SET model curve based on the orthodox theory, with the inclusion of asymmetric junction resistances, $R_1=0.3R_2$. The linearity at low bias voltages for maximum current indicates that the leads in the SET are normal, for otherwise there would be a gate-independent zero-current region for $|eV_{\text{bias}}|<2\Delta$. This is further supported by Fig. 2(c), which shows $I_{\text{SET}}$ as a function of both $V_{\text{bias}}$ and $V_g$, demonstrating the Coulomb diamonds characteristic to a normal SET.

Another more demanding test of the quality of a proximized junction is to utilize them in a NIS junction. The magnitude of subgap features, such as supercurrent through the junction, is an excellent indicator for determining the superconductivity of the Al dot. Also the differential conductance of the junction at low $T$ is directly proportional to the superconductor density of states if the counterelectrode is at normal state. The NIS junction samples are fabricated like the NIN junctions of the SET described earlier, with Al as the S lead and copper as the N lead, yet these could be replaced by other normal and superconducting metals.

Several NIS junctions were fabricated simultaneously with various $L_0$, the length of Al dot uncovered by the normal electrode. The NS contact and tunnel junction overlap areas were kept constant. The inset of Fig. 3(a) shows a scanning electron micrograph (SEM) image of the structure with the shortest $L_0=95$ nm. The measured normal-state resistances $R$ of the junctions were in the range of 35–75 kΩ and the zero temperature superconductor energy gap of the S–Al was $\Delta=220$ μeV. Figure 3 shows the measured current-voltage (IV) characteristics at $T=65$ mK. Additionally, Fig. 4 shows the differential conductance of several samples obtained by numerical differentiation of the IV data together with a theoretical fit for a standard NIS junction. Finally, the IV characteristics of the $L_0=95$ nm sample in the temperature range of $T=43$–675 mK are plotted in Fig. 5, together with theoretical curves using a phenomenological Dynes parameter $\gamma=1.5 \times 10^{-4}$ in the Al quasiparticle density of states.

In these figures the dependence on the length of the Al dot is clearly visible: with $L_0=200$ nm they appear to have mixed NIS and SIS junction properties with notable supercurrent peaks, but as the dot length approaches 100 nm, both
the IV curve and the differential conductance resemble increasingly those of a regular NIS junction. The results suggest that proximized Al tunnel junctions provide a valid tool for fabricating NIS junctions, where the superconductor is not necessarily aluminum. Such structures have been a challenge to fabricate by shadow evaporation till now.

Concluding, the method of forming tunnel junctions with the help of laterally proximized Al was introduced. These junctions were implemented in a fully normal SET and individual NIS junction configurations. The measured IV characteristics would indicate that the presented method is likely to allow shadow fabrication of high-quality NIN junctions, as well as NIS junctions with non-Al superconductor.

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