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Mappings of Magnetic Field and Current Density Using Nano Superconducting Quantum Interference Device Microscope

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Abstract

A scanning nano-superconducting quantum interference device (SQUID) microscope is a powerful tool for high sensitivity probing of magnetic field distribution. Here, we report on reconstruction of two-dimensional current density distribution and on characterization of superconducting properties of tungsten-carbide films prepared by focused-ion-beam chemical vapor deposition by our scanning nano-SQUID microscope.

1. Introduction

Nano-superconducting quantum interference devices (SQUIDs) have received considerable attention recently [1] as a method to characterize properties of semiconductor and superconductor nanostructures. Weak-link Dayem Josephson junction nano-SQUIDs are favorable to reduce the size of the SQUID loop, however, hysteresis is often observed in current-voltage characteristic of weak-link nano-SQUIDs [1] that is not suitable for application to scanning microscope. We have recently succeeded in developing a weak-link nano-SQUID scanning microscope with a Nb nano-SQUID probe with small hysteresis that can be operated as a magnetic flux to voltage transducer [2]. Here we report on our investigations on reconstruction of current density distribution in a Hall-bar structure of a two-dimensional electron gas in a modulation-doped single heterojunction, and on the properties of tungsten-carbide superconducting films prepared by focused-ion-beam chemical vapor deposition (FIB-CVD) [3] revealed by using our Nb weak-link scanning nano-SQUID microscope.

2. Experimental

Nb nano-SQUID probes have been fabricated by a maskless laser lithography followed by milling by a focused ion beam (FIB) process. The dimensions of the SQUID loop and the weak-link width were 1.0 µm and 80 nm, respectively. The samples were scanned using closed loop inertially-actuated triaxial stepping piezoelectric-stages with resistive position encoders. A quartz tuning fork was used to monitor the distance between the nano-SQUID probe and the sample surface. Measurements were conducted in a cryogen-free pulse tube refrigerator with base temperature of 3.4 K. Perpendicular magnetic field to the sample surface was applied using a superconducting magnet with the bore size of 50 mm. The details of the scanning nano-SQUID microscope can be found elsewhere [2].

We used a GaAs/$Al_{0.3}Ga_{0.7}As$ modulation-doped single heterojunction Hall-bar structure as shown in Fig. 1(a). The two-dimensional electron gas is located 80 nm from the surface. The density and the mobility of the two-dimensional electron gas were 3.3×10^{15} m^{-2} and 91 m^2/Vs, respectively, at 2.8 K.

W-C films with thickness of 300 nm were grown on a p-Si substrate using tungsten hexacarboxyl ($W(CO)_6$) precursor by FIB-CVD. Nb/Au electrodes were fabricated by electron beam lithography with thicknesses of Nb and Au of 600 and 30 nm, respectively. A scanning electron microscope image of W-C films and Nb/Au wires is shown in Fig 2.

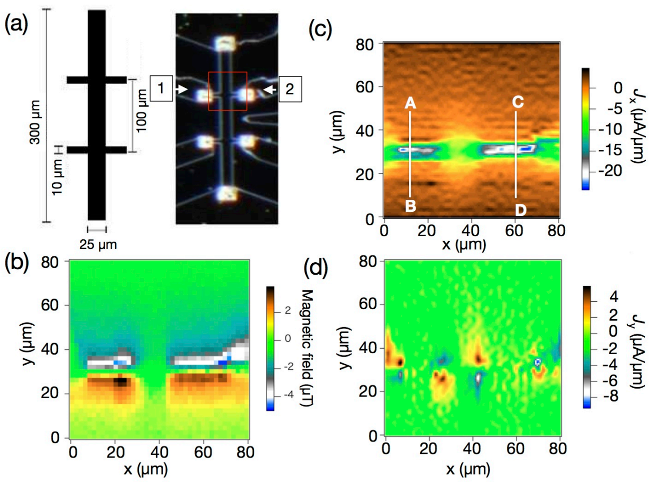

Fig. 1 (a) Schematic structure of a sample Hall-bar and optical micrograph of a sample Hall-bar structure. Red square indicates the scanning area of 80 µm×80 µm. (b) Mappings of magnetic field distribution induced by current in a GaAs/$Al_xGa_{1-x}As$ modulation-doped single heterojunction sample at T=4 K for current I_{sample} = 70 µA. (c) Reconstructed current density distributions J_x (x, y) and (d) J_y (x, y) from (b) [2].

2. Results and discussions

Imaging of current density in a modulation-doped single heterojunction

Figure 1 (b) shows a mapping of magnetic field created by ac current between the voltage probes 1 and 2 of the Hall-bar structure of GaAs/AlGaAs modulation-doped single heterojunction at I_{sample} = 70 μA at 4 K. The size of the scanning area was 80×80 μm^2 with a step size of 2 μm for x- and y-directions. The positive and negative magnetic fields are observed near the edges of the stem of the Hall-bar structure.

Current density distribution $\mathbf{J}(x,y)$ has been reconstructed from the measured magnetic flux distribution based on a Fourier analysis by assuming that currents are restricted to two-dimension [2,4]. A Parzen window was used to eliminate high-spatial-frequency components of the measured mapping. The reconstructed two-dimensional current density is shown in Figs. 1(c) and (d). We can see that the current density $J_x(x, y)$ spreads to the wider bar in the center, where the stem crosses the vertical bar. This is more clearly indicated in $J_y(x, y)$ in Fig. 1(d) by the positive and negative current density near the corners of the mesa structure of the Hall-bar. Most of these features are reproduced by a calculated current density, and deviation was explained by ballistic electron transport [2]. The current obtained by integrating $J_x(x, y)$ on the white bars in Fig. 1(c) is 84 and 91μA for the crosssection A-B and C-D, respectively, in reasonable agreement with I_{sample} = 70 μA.

Imaging of magnetic field around tungsten-carbide films

FIB-CVD of superconducting W-C films is a promising technique to fabricate superconducting devices such as nano-SQUIDs by direct writing without lithography. We have carried out mappings of magnetic field distribution around W-C films in an external magnetic field and mappings of magnetic field created by current density flowing in W-C strips in an aim to explore superconducting properties of W-C films.

Temperature dependence of resistance of a W-C strip indicated zero resistance below 5.5 K at 0 T. The superconducting transition temperature T_c as defined by 10% of resistance drop from the resistance at the normal phase was 5.9 K. The Ginzburg-Landau coherence length was estimated to be 5.8 nm.

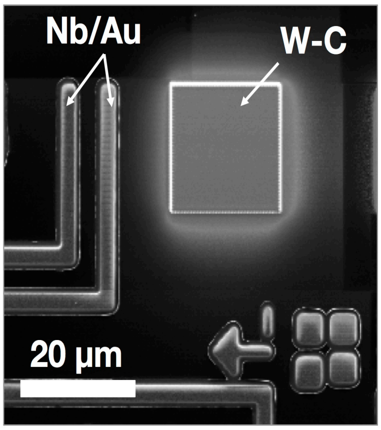

Fig. 2 Scanning electron microscope image of Nb/Au wires and FIB assisted tungsten carbide film. The thickness and the size of the tungsten carbide film was 300 nm and 20 μm × 20 μm, respectively.

Mapping of magnetic field clearly indicated reduction of magnetic field due to Meissner effect of the superconducting Nb wire in external magnetic field of ~0.171 mT at 4.3 K. We have found that the reduction of magnetic field on the square $20 \times 20\ \mu m^2$ W-C film as shown in Fig. 2 was small. This result was compared with calculated magnetic field distribution around Nb and W-C films base on the London equations using a finite element method. We have found that the measured reduction of magnetic field is qualitatively reproduced by calculated magnetic field distribution with vortices penetrating the W-C films.

In Fig. 2, gray area is seen around the square designed region of the W-C film. In order to estimate the current flow in this area, we have performed mappings of magnetic field created by current density flowing in simultaneously deposited W-C strips. The reconstructed two-dimensional current density indicates that the current flows primarily in the designed area of the W-C strip and small contribution from the unintentionally deposited area.

3. Conclusions

We have demonstrated that scanning nano-SQUID microscope is a powerful tool for probing magnetic field and current density distributions. Our scanning nano-SQUID microscope may contribute to characterize, for example, topological insulators and superconductors.

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