Evidence for Supercurrent Quantization in Interfacial Josephson Junctions

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We observe a series of discontinuities in the above gap current-voltage characteristics of highly transmissive Nb/Si superconductor-semiconductor interfaces. The bias at which each switch occurs decreases in quantized steps as a function of temperature and magnetic field. The observed step size is the same for both dependencies. We propose that the steps correspond to supercurrent quantization through granular Josephson junctions formed near the interface. [S0031-9007(97)05103-X]

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The conductance through a quantum point contact in a two-dimensional electron gas (2DEG) is quantized to $2e^2/h$ times the number of transmitted one-dimensional channels [1]. Analogous behavior is predicted for a small area Josephson junction formed by a narrow constriction between two superconductors [2]. In this case, quantization is in the critical current, and is given by $e\Delta_0/\hbar$ times the number of transmitted one-dimensional channels, where Δ_0 is the pairing potential of the superconductor. Recently, Takayanagi *et al.* [3] fabricated the first working superconducting quantum point contacts, using Nb contacts to a submicron width InAs 2DEG, modulated by a split gate. They observed steps in both the critical current and the normal conductance as a function of gate bias. However, substantial fluctuations were observed in the step height, and the critical current was not quantized at the theoretically predicted values. Muller *et al.* [4] measured the conductance and critical current through a break junction of Nb. They observed steps in the critical current consistent with the theoretically predicted value. More recent experiments [5] imply, however, that such steps might be caused by abrupt atomic rearrangements, which change the normal resistance [6].

This paper presents intriguing new evidence for the quantization of the critical current in small area Josephson junctions. We perform detailed measurements of the interface resistance of Nb/Si junctions. Below a transition temperature of 1.5 K, we observe a series of switches in the above gap dc current-voltage characteristics. As the temperature increases towards the transition, or as a magnetic field is applied, the switching bias decreases in a series of quantized steps. The observed step size is equal in both temperature and magnetic field dependencies. We propose that the switches occur as we exceed the critical supercurrent of Josephson junctions formed between Nb_3Si particles and the Nb contact. By varying the temperature or magnetic field we are able to reduce the junction area, and observe a corresponding quantized change in the critical current.

Figure 1(a) shows a schematic drawing of our Nb/Si junctions. A Nb contact is made to a 53 nm thick single crystal n^{++} Si layer which has been wafer bonded to 100 nm of SiO_2 on a p^+ Si substrate. 2.0 K Hall measurements of the Si layer indicate that the carrier density $n = 5.3 \times 10^{25}$ m^{-3} and the elastic scattering length $l_e = 10.8$ nm. We create a highly transmissive interface by first sputter etching the Si surface at 200 W

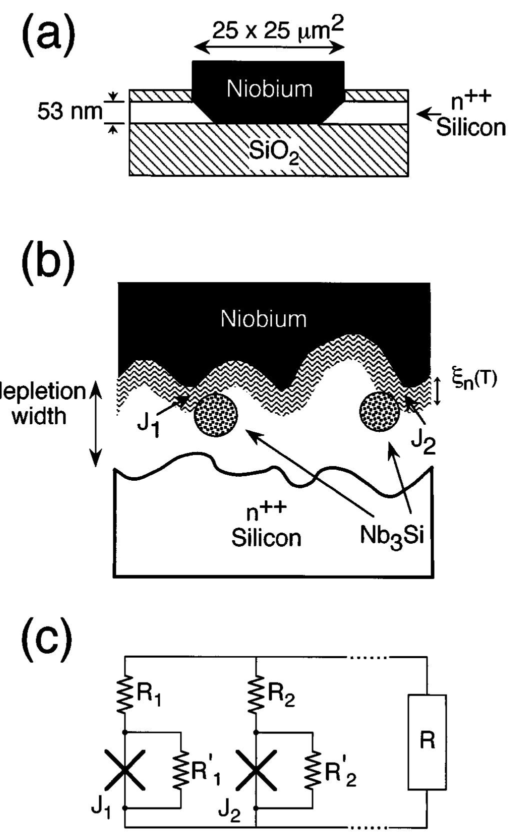

FIG. 1. (a) Schematic drawing of our Nb/Si junctions. (b) A representative region of the Nb/Si interface. Nb_3Si particles, which form during Nb deposition, provide additional tunneling pathways. At low enough temperatures the normal coherence length ξ_n extends to create Josephson junctions J_1 and J_2. (c) Circuit model of the Nb/Si interface. The Nb_3Si Josephson junctions J_n have normal state resistances R_n' and lie in series with the Nb_3Si/Si interface resistances R_n. The in-parallel Schottky barrier resistance is R.

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for 10 min in an Ar pressure of 3×10^{-2} mbar. This removes a 25 μm × 25 μm square of the (100) Si top layer, and exposes clean (111) Si side surfaces. Without breaking the vacuum we then deposit 180 nm of Nb, resulting in a total Nb/Si contact area of approximately $A_c = 6\ \mu\text{m}^2$. We measure the critical temperature of our Nb to be $T_c = 9.0$ K, indicating a high quality film. Four-terminal measurements of the Nb/Si junction resistance are made via Ag contacts to the Si, and Au contacts to the Nb. The effects we describe below have been observed in four different devices, each fabricated using the same method.

In the inset in Fig. 2, the differential resistance (dV/dI) of a typical junction is plotted as a function of applied bias. Measurements at three temperatures (1.6, 1.2, and 0.35 K) are shown, normalized with respect to the resistance at high bias. In each trace, there is a broad dip in dV/dI corresponding to the Nb gap energy ($\Delta_0 = \pm 1.6$ meV). Further measurements (not shown) demonstrate that the dip survives up to the Nb transition temperature. This dV/dI feature has been reported by a number of groups [7,8] and can be attributed to Andreev reflection at the Nb/Si interface [9,10]. In the 0.35 K trace we also observe a strong subgap resistance dip. (This first appears at temperatures below 1.1 K.) A similar feature was reported by Heslinga *et al.* [7] and attributed to the appearance of a "proximity induced gap," in the Si layer. More simply, the RSJ (resistively shunted junction) model predicts that a subgap dip can be observed if a Josephson junction forms in parallel with the interface resistance [11].

In our case, a possible explanation for the subgap resistance dip is suggested by the temperature dependence of dV/dI at zero bias (not normalized), plotted in the main part of Fig. 2. The differential resistance decreases sharply at a temperature $T_1 = 1.5$ K, from 890 to 480 Ω. This drop, which strongly resembles a superconducting transition, occurs at the reported transition temperature of Nb_3Si [12]. If we assume that the ratio between the transition temperature T_1 and the gap energy Δ_{Nb_3Si} equals that for Nb, then $\Delta_{Nb_3Si} = 0.25$ meV. This is similar to the observed resistance dip width of ±0.28 mV at $T = 0.35$ K. These results imply that the subgap feature is due to Andreev reflection from Nb_3Si particles that form near the interface during fabrication. Nb_3Si has a high eutectic temperature (645 °C), but it has been shown that Nb diffuses nonuniformly into Si at our maximum process temperature of 300 °C (immediately following the sputter etch), and forms small intermixed regions [13]. We also measured junctions made without the sputter etch, and these showed no subgap dip or resistance transition.

Figure 3(a) gives results of a four-terminal dc measurement of the Nb/Si interface (see inset) at 1.6 and 0.35 K, corresponding to temperatures above and below the transition temperature, T_1. At $T = 1.6$ K, the I-V curve has a weak Schottky barrier dependence. At $T = 0.35$ K, the

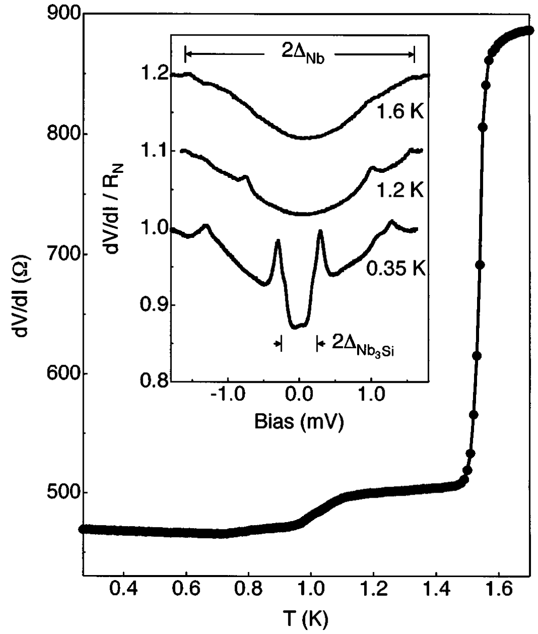

FIG. 2. Zero-bias differential resistance of a highly transmissive Nb/Si junction versus temperature. A resistance drop occurs at 1.5 K, the Nb_3Si transition temperature. Inset: The normalized differential resistance versus bias at 1.6, 1.2, and 0.35 K. The 1.2 and 1.6 K traces are offset by 0.1 and 0.2, respectively. The gap widths for Nb and Nb_3Si are indicated.

current rises above the 1.6 K value, as expected from the results of Fig. 2. As the applied bias increases, the measured current and voltage switch discontinuously due to a sudden increase in the interface resistance. A total of six switches is observed with increasing bias, until the above and below transition I-V characteristics are almost identical. In Fig. 3(a), we also plot the 0.35 K characteristic measured with a transverse magnetic field of $B = 1.0$ T (dashed line). The I-V is almost identical to the above transition trace measured at 0 T—only a small excess current is observed at low bias. We note that these results are completely reproducible, and that nonreproducible noise due to heating is not observed until the current >200 μA.

In Fig. 3(b), we plot a series of 26 I-V characteristics for temperatures between 1.6 and 0.35 K. The lowest lying trace corresponds to $T = 1.6$ K. The traces above this correspond to the temperatures $1.55, 1.50, \ldots,$ 0.35 K and are offset by $0.25, 0.50, \ldots, 6.25$ μA, respectively. Plotted in this way, the resistance switches reveal a remarkable temperature dependence. As the temperature increases from 0.35 K, the bias at which each switch occurs decreases discontinuously, in a series of steps. For any particular switch, the step width is approximately constant. If we consider the three most clearly defined switches (marked S_1, S_2, and S_3), the average width of the first four steps is $dV_1 = 1.60$, $dV_2 = 1.82$, and $dV_3 = 2.04$ mV, with a maximum variation (per switch) of 3%. The steps can be seen more clearly if the switching bias V_n is plotted as a function

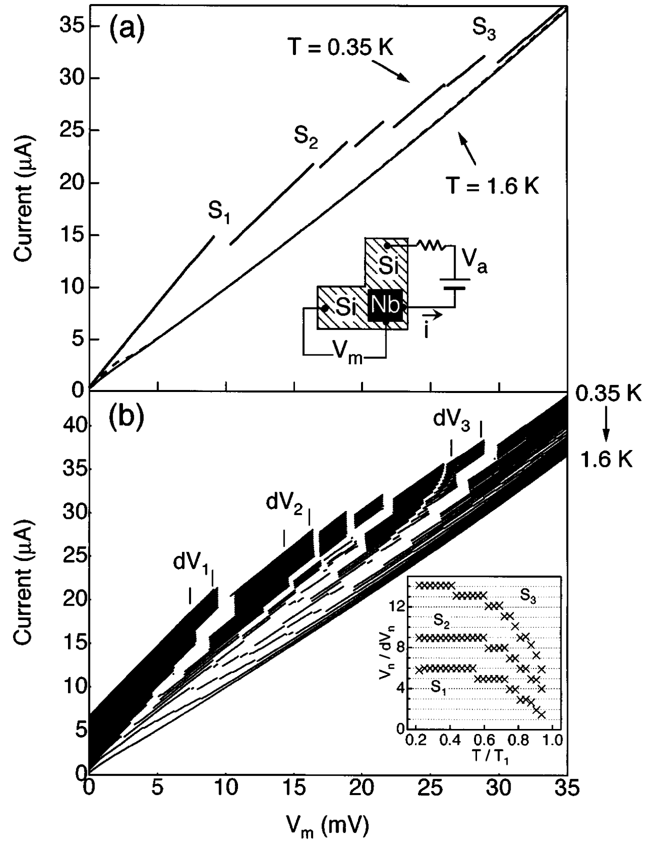

FIG. 3. (a) Four-terminal measurement of the dc current and voltage across the Nb/Si interface at $T = 0.35$ and $T = 1.6$ K. Each trace shows measurements made at 1000 equally spaced values of the applied bias V_a (see inset). The dashed line shows the characteristics for $B = 1.0$ T and $T = 0.35$ K. (b) dc current and voltage characteristics plotted for 26 equally spaced temperatures between 0.35 and 1.6 K. The traces are offset for clarity. Inset: The normalized switching bias as a function of reduced temperature for the three switches indicated.

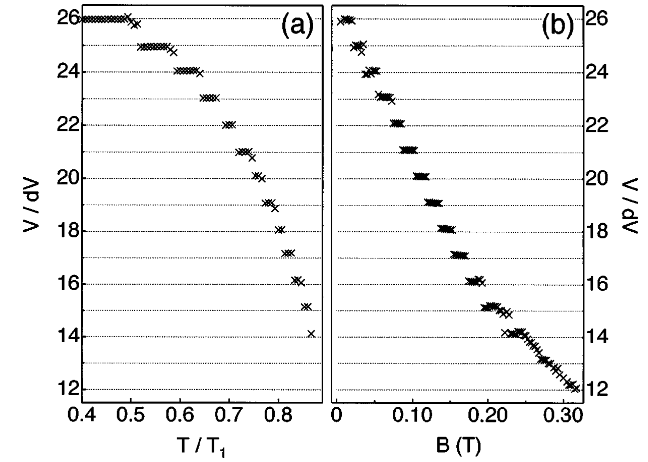

FIG. 4. The normalized switching bias as a function of (a) reduced temperature and (b) magnetic field for a typical resistance switch.

of temperature. This is shown in the inset in Fig. 3(b), where V_n is plotted for the three switches S_1, S_2, and S_3 as a function of the reduced temperature T/T_1. The biases are normalized by the average step widths, dV_n. In each case, three or more equally spaced steps are observed. As the temperature approaches T_1, the switches merge together.

Further measurements provide more convincing evidence for the quantization of the switching bias. Figure 4(a) shows the normalized switching bias as a function of temperature taken from observations of the lowest bias switch in a second device. These points are compiled from a set of 94 I-V measurements [similar to those shown in Fig. 3(b)] taken at equally spaced temperatures between 1.30 and 0.37 K. A total of 12 well-defined steps is observed, each containing at least three bias points. The average step width, dV, is 0.42 mV. We point out that four other switches were observed in this device, and each showed a similar temperature dependence, although dV is different for each switch.

We also studied the influence of magnetic field on the switching bias. Figure 4(b) shows the normalized switching bias for the switch shown in Fig. 4(a) as a function of magnetic field perpendicular to the current path. These points were compiled from a set of 130 I-V measurements taken at magnetic fields equally spaced between 0 and 0.33 T ($T = 0.37$ K). The data clearly show that the switching bias is also quantized as a function of magnetic field. We observe 12 well-defined steps each containing six or more B-field points. The bias is again normalized using $dV = 0.42$ mV. For $B > 0.25$ T, the steps disappear, and the switching bias decreases continuously with magnetic field. Most remarkably, a comparison between Figs. 4(a) and 4(b) shows that the quantized step size is equal to the same value in the B dependence as in the T dependence. The background T and B dependencies, however, are clearly different. Similar results were observed in all five switches of this device.

To understand these results, we consider the Nb/Si interface in more detail [see Fig. 1(b)]. Current flows across the interface by electron tunneling through the Si depletion region. Because of the high doping density, the average interdopant spacing ($n^{-1/3} \approx 2.7$ nm) is comparable to the depletion width (3.7 nm) [14]. In this case, the depletion width varies substantially across the contact and significant transmission occurs only at the most transparent sections of the interface [15]. We calculate the approximate area of the transparent regions as follows. The average transmission coefficient per quantum channel is given by $t_{\mathrm{av}} = R_S/R_j$, where R_S is the Sharvin resistance and R_j is the measured junction resistance. From Fig. 2, R_j at 1.6 K $= 890\ \Omega$, and R_S for our contact is 20 mΩ so that $t_{\mathrm{av}} = 2.3 \times 10^{-5}$. On the other hand, a fit of the normalized dV/dI dip at 1.6 K gives a transmission coefficient for the transparent regions of $t_A = 0.84$ [10]. The maximum area of the transparent regions is then approximately $A_T = A_c \times (t_{\rm av}/t_A) = 164\ {\rm nm}^2$, where A_c is the total contact area. Below the transition, at $T = 1.2$ K, the resistance drops to $R_j = 480\ \Omega$, but the size of the normalized dip in dV/dI remains roughly the same (see inset, Fig. 2). This means that t_A stays constant, while the transmissive area increases to approximately $164\ {\rm nm}^2 \times (890\ \Omega/480\ \Omega) = 304\ {\rm nm}^2$.

The switches observed in Fig. 3 progressively transform the $T < T_1$ resistance (0.35 K) into the $T > T_1$ resistance (1.6 K) with increasing bias. Each switch is thus a partial breakdown of the transmissive area added at T_1. Although, Joule heating could perhaps raise the temperature locally above T_1 [16], this does not explain the quantization in the temperature dependence seen in Fig. 4. Phase-slip processes in granular superconducting films [17] can also produce resistance steps; however, such steps are independent of small magnetic field, and smear out continuously with increasing temperature [18,19].

We instead propose that our switches are due to the critical current transition of individual nanometer scale Josephson junctions formed between Nb_3Si particles and the Nb contact. The current pathway through a particular silicide particle, n, is given by a Josephson junction J_n in series with a Nb_3Si/Si interface resistance R_n [see Fig. 1(c)]. In the superconducting state, the Josephson junction resistance is zero, and the current through J_n is simply $I_n = V/R_n$. The switching bias is thus proportional to the current carried by the Josephson junction at the critical current transition and should be quantized to $V = Ne\Delta_0/R_n\hbar$, where N is the number of one-dimensional transmitted channels, and $e\Delta_0/R_n\hbar$ is equal to the quantized step size dV. In our case, $N = k_F^2 A/4\pi$, where A is the cross-sectional area of the junction. The observed quantization is thus produced if A decreases with the normal coherence length as a function of increasing B and T.

In this model, the number of modes N is equal to the normalized switching bias V/dV. From the maximum number of modes, we can calculate the approximate cross-sectional area A_n of the particles corresponding to the three switches S_1, S_2, and S_3 in Fig. 3. This gives $A_1 = 56$, $A_2 = 84$, and $A_3 = 131\ {\rm nm}^2$, roughly corresponding to the cross-sectional area determined from our simple estimate above ($140\ {\rm nm}^2$), and giving an average particle radius on the order of λ_F.

We expect that, in the limit of large N, the T and B dependencies in Fig. 4 should be described by $I_c(T,B)$ for a large area point contact. The envelope of our quantized T dependence appears similar to $I_c(T)$ for a large area device [20], while the envelope of the quantized B dependence resembles the low field behavior of a screened Josephson junction [11]. The field required to insert a single flux quantum in such small junctions ($\sim 100\ {\rm nm}^2$) is larger than the critical field of Nb, so that no oscillatory dependence is expected. A detailed understanding would require a rigorous analysis of $I_c(T,B)$ in the crossover between macroscopic and nanoscale junctions.

In conclusion, we observe evidence that the maximum supercurrent through Josephson junction pathways formed near a Nb/Si interface is quantized, in agreement with theoretical predictions. This could provide a new and straightforward way to study supercurrent transport in nanometer-scale Josephson junctions.

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