Dissipation-Driven Superconductor-Insulator Transition in a Two-Dimensional Josephson-Junction Array

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We have fabricated a two-dimensional array of Josephson junctions within 100 nm of a two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure. The screening provided by the 2DEG causes the array to show superconducting behavior despite a large junction resistance. Varying the resistance per square of the 2DEG changes the dissipation in the electrodynamic environment of the array independently of any other parameters in the system. As the resistance increases, the current-voltage characteristics of the array change from superconducting to insulating in character. [S0031-9007(97)02822-6]

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A variety of diverse physical systems, including granular [1] or homogeneous [2] thin films, two-dimensional (2D) Josephson-junction arrays [3], and high temperature superconductors [4] undergo a superconductor-insulator (S-I) phase transition as a characteristic resistance of the system in its normal state increases through a critical value on the order of the resistance quantum $R_Q = h/4e^2 \approx 6.45\ \mathrm{k}\Omega$. The transition is quantum mechanical in nature: the increasing normal state resistance is associated with an increase in quantum fluctuations of the superconducting phase. Eventually, these fluctuations destroy global phase coherence and lead to an insulating state. It has been suggested [5–8] that the S-I transition in these systems could be driven by changes in dissipation; however, there appears to be no unambiguous supporting evidence. In thin films disorder plays a strong role, and recent theoretical work treating these systems as charge-$2e$ bosons moving in a random 2D potential [9] has been met with substantial experimental verification [2,10]. Furthermore, the physical origin of the dissipation is unclear. In the case of Josephson junction arrays, although quasiparticle tunneling [5] at energies large compared to the superconducting gap produces dissipation characterized by the normal state resistance R_N, it is unlikely that the relevant energy scales are so large [3,11]. At lower energies, quasiparticle dissipation is negligible since the subgap resistance is much larger than R_N. In high temperature superconductors, it has been proposed [8] that an interpenetrating fluid of normal electrons produces the dissipation. However, radiation damage inflicted to increase the normal state resistance probably also increases the disorder and reduces the density of superconducting electrons.

In this Letter, we describe the unambiguous observation of a dissipation-driven S-I transition. The sample was a specially designed and fabricated 40×40 Josephson junction array for which we can continuously vary the dissipation associated with the local electrodynamic environment independently of any other relevant parameters. To provide the variable dissipation, we fabricated the array on a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure in which a 2D electron gas (2DEG) is located approximately 100 nm from the surface (see Fig. 1). The heterostructure was grown on a GaAs substrate using molecular beam epitaxy and consists of the following layers: 500 nm of GaAs, 92 nm of $Al_{0.3}Ga_{0.7}As$, and 8 nm of GaAs. The $Al_{0.3}Ga_{0.7}As$ is selectively doped with Si donors situated 32 nm from the

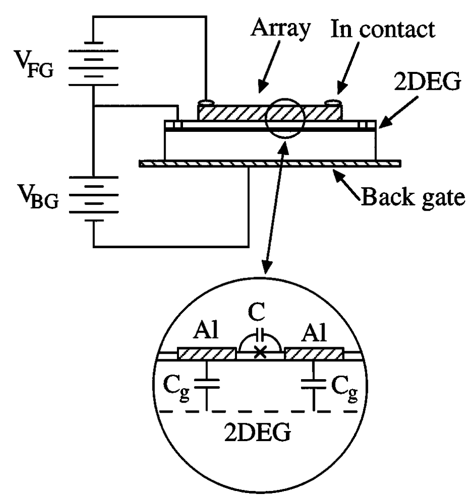

FIG. 1. Schematic diagram of an array with variable dissipation. The array is fabricated on a GaAs/$Al_{0.3}Ga_{0.7}As$ substrate in which a 2DEG is located approximately 100 nm below the surface. Pressed and alloyed In contacts are made to the array and 2DEG, respectively. A voltage V_{BG} between the back gate and 2DEG increases its resistance per square. A voltage V_{FG} between the array in the normal state and 2DEG allows independent monitoring of the capacitance to ground C_g.

lower $GaAs/Al_{0.3}Ga_{0.7}As$ interface, at which the 2DEG forms. The substrate is placed on a metallic back gate. We bias the back gate negatively relative to the 2DEG with a large voltage V_{BG} to change the sheet density n_s of electrons in the 2DEG, and thereby change its resistance per square R_g. To reduce the required voltage, we thinned the substrate to a thickness of about 230 μm. The array consists of Al islands linked in a square lattice by $Al/Al_xO_y/Al$ tunnel junctions, fabricated using electron-beam lithography and shadow evaporation [12]. The array is characterized by the normal state tunneling resistance R_N and capacitance C of the junctions, and the capacitance C_g of each island to the 2DEG. The island areas are sufficiently large that $C_g \gg C$. We estimate the Josephson-coupling energy E_J at zero temperature through the relation [13] $E_J = \pi\hbar\Delta/4e^2R_N$, where Δ is the superconducting gap. The charging energy E_C of an isolated junction is $E_C = e^2/2C$. The capacitance to ground and junction capacitance determine the energy $E_{C_\Sigma} = e^2/2C_\Sigma$ to transfer electrons between neighboring islands; here $C_\Sigma \approx (C_g + 5C)/4$ [14]. In the absence of Josephson coupling, we expect a Coulomb gap to appear on the I-V characteristics at a voltage $\pm eN/2C_\Sigma$, where N is the number of islands in series.

Previously, Geerligs *et al.* studied similar arrays without a ground plane, and spanned the S-I transition with a series of arrays with different R_N [3]. In that work, the S-I transition was driven primarily by competition between E_C and E_J. Because the charge Q on a junction and the phase difference ϕ across it are conjugate variables they satisfy an uncertainty relation $\Delta\phi\Delta Q \geq 2e$. When the ratio $x \equiv E_C/E_J$ is large, charge is the good quantum variable and phase fluctuations are large, preventing superconductive coupling [15]. Numerous theoretical investigations of arrays, including those based on the quantum XY model [16] as well as those which include the effects of capacitance renormalization due to virtual quasiparticle tunneling [11], have predicted the destruction of global phase coherence for $x \gtrsim 1$. The results of Geerligs *et al.* [3] suggest a critical value of x between 1.5 and 2.5.

In the presence of a ground plane of normal electrons we must compare the Josephson energy E_J with the island charging energy E_{C_Σ}, which is significantly smaller than E_C when $C_g \gg C$. We must also consider the dissipation associated with the resistance per square R_g of the ground plane. In the heat-bath formalism of Caldeira and Leggett [17], dissipation introduces damping of phase fluctuations that is inversely proportional to the resistance of the electrodynamic environment [6,7]. We therefore expect that when R_g is small, phase fluctuations will be heavily damped and a large value of C_g should promote global superconductivity. When R_g is large, the 2DEG will not effectively damp phase fluctuations and in the proper circumstances insulating behavior may result, even if C_g is large. In our experiment, we can vary the dissipation continuously *in situ* without varying any other parameters, and span the S-I transition with a single sample at zero magnetic field and fixed temperature.

We made electrical measurements of the array in a dilution refrigerator at temperatures between 25 and 800 mK, using a four-probe technique. The sample leads were carefully filtered by microwave [18] and radio-frequency filters at 4.2 K, and by a second set of microwave filters at the mixing chamber temperature. The measurement electronics were battery powered, except for a microcomputer which collected the data. Radio-frequency π filters at room temperature rejected any digital noise. We performed all measurements in a screened room, with a mu-metal shield around the sample space. We measured R_g using a van der Pauw technique, and obtained the sheet density n_s from Shubnikov–de Haas oscillations at magnetic fields of 0.1 to 0.3 T. At $V_{BG} = 0$ V, n_s was 2.05×10^{11} cm^{-2}, the mobility was 1.9×10^5 cm^2/V s, and $R_g = 170\ \Omega/\square$. At the maximum applied gate voltage of $V_{BG} = 540$ V, n_s decreased to 0.7×10^{11} cm^{-2} while R_g increased to 2570 $\Omega/\square$. We expect that the 2DEG is continuous and uniform for n_s in this range.

We carefully chose the parameters of the array so that it would be insulating in the absence of a ground plane. We obtain $R_N = 23.4$ kΩ from the inverse slope of the I-V characteristic at high current bias when the array was driven normal by a 0.4 T magnetic field. Combining R_N with the measured value of $2\Delta = 0.35$ meV we estimate $E_J/k_B \approx 0.28$ K. From the measured junction area of 0.005 μm^2 and work of other groups [3] implying a specific capacitance of 100 fF/μm^2 for junctions with similar area and resistance we estimate $C \approx 0.5$ fF. We obtain a charging energy $E_C/k_B \approx 1.9$ K, so that in the absence of a ground plane $x \approx 6.8$, and the array would be insulating at low temperatures [3].

To measure C_g we bias the array, driven normal with a magnetic field, with a small current (about 85 pA) and measure changes in the voltage across the array as a function of the voltage between it and the ground plane V_{FG} (see Fig. 1). The array voltage is periodic in V_{FG} with period e/C_g. To determine C_g accurately, we measured the power spectrum of the oscillations; the position of the peak yielded $C_g = 2.96 \pm 0.04$ fF. We also checked for electrical isolation between the array and 2DEG while varying V_{FG}, and found the leakage resistance to be in excess of 10 GΩ. Using the above values of C and C_g we obtain $E_{C_\Sigma}/k_B \approx 0.68$ K [14]. The ratio $E_{C_\Sigma}/E_J \approx 2.4$ suggests that the array may show superconducting behavior for sufficiently small R_g.

In Fig. 2 we show the current-voltage (I-V) characteristics for the array for a series of back-gate voltages, at $T = 25$ mK and in zero magnetic field. We define the zero-bias resistance R_0 as the inverse slope of the I-V characteristic at zero current and voltage. Since the array is square, R_0 is equivalent to the resistance per square. When $V_{BG} = 0$ V and R_g is small (170 $\Omega/\square$), the I-V

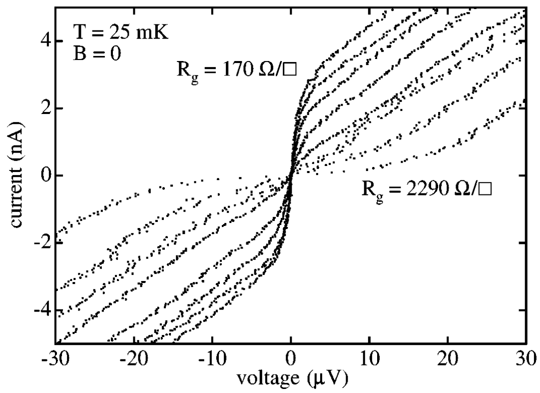

FIG. 2. I-V characteristics of the array at zero magnetic field and $T = 25$ mK, for eight back-gate voltages $V_{\mathrm{BG}} =$ 0, 100, 200, 300, 400, 450, 500, and 525 V, corresponding to ground plane resistances of $R_g = 170$, 240, 360, 570, 990, 1350, 1900, and 2290 $\Omega/\square$. For $R_g = 170\ \Omega/\square$, the I-V characteristic is clearly superconductorlike, while for $R_g = 2290\ \Omega/\square$ it has become insulatorlike and shows a clear Coulomb gap. The nature of the I-V characteristic can be varied continuously between these two extremes by changing V_{BG}.

characteristic is clearly superconductorlike, showing a small but clear "supercurrent," with low R_0. However, when we increase R_g to 2290 $\Omega/\square$ by applying a large back-gate voltage, the I-V characteristic changes dramatically: the supercurrent is completely suppressed, and a small (compared to $eN/2C_\Sigma$) but pronounced Coulomb gap appears. The I-V characteristic changes smoothly between these two extremes as we increase V_{BG}, with the supercurrent shrinking and R_0 increasing. The transition from superconductor- to insulatorlike behavior occurs over a narrow range in V_{BG} of about 20 V. It is interesting to note that at the center of the transition, when the I-V characteristic shows neither a supercurrent nor a charging gap, we measure $R_0 \approx 6.5\ \mathrm{k}\Omega/\square$. This is consistent with recent theories [9] which predict a universal value on the order of R_Q for the zero-temperature resistance of a system of charge-2e bosons at the S-I transition.

Applying a back-gate voltage clearly cannot change the junction capacitance. However, it is conceivable that varying V_{BG} could change C_g, either due to motion of the center of mass of the 2DEG, or in the case of extreme depletion due to the breakup of the 2DEG itself. To investigate this possibility, we measured C_g for several different values of V_{BG}, to a maximum of 500 V. To within the experimental accuracy of our measurement (± 0.04 fF), there was no change in the value of C_g. We also verified that the tunneling resistance R_N was independent of V_{BG}. As mentioned above, the 2DEG is not expected to show significant nonuniformity in the range of n_s covered in our experiment. We estimate the average number of electrons in the 2DEG per unit cell, with an area of 4.7 $\mu\mathrm{m}^2$, decreases from about 9600 to 3300 as V_{BG} changes from 0 to 540 V, so that fluctuations in the number of screening electrons per unit cell are at worst about 2%. The fact that C_g is independent of V_{BG} also argues against any breakup of the 2DEG. Finally, when we measure the I-V characteristics in the superconducting state, the array and 2DEG are electrically connected, so that V_{BG} induces electric fields only between the back gate and the 2DEG. We conclude that applying a back-gate voltage changes only R_g of the ground plane, that is, the dissipative electrodynamic environment of the array, and no other relevant physical parameters.

Plotting R_0 versus R_g on semilog axes as shown in Fig. 3, we see that R_0 increases exponentially with R_g. We show R_0 versus R_g (markers) and fits (solid lines) of the data to the form $R_0 = R_1 \exp(R_g/R_2)$ at 25, 50, 100, and 150 mK. At $T = 25$ mK, the array is extraordinarily sensitive to R_g: increasing R_g by a factor of 16 leads to an increase in R_0 of over 2 orders of magnitude. This extreme sensitivity diminishes at higher temperatures, until at 150 mK R_0 depends only weakly on R_g. The values of the fitting parameters are $R_1 = 272$, 162, 205, and 1390 Ω and $R_2 = 443$, 556, 913, and 1830 Ω for the four temperatures above, respectively.

The inset to Fig. 3 shows the temperature dependence of R_0 for $R_g = 170\ \Omega/\square$ and $R_g = 2290\ \Omega/\square$. At low temperatures, for $R_g = 2290\ \Omega/\square$ the array is clearly insulating with R_0 increasing by 2 orders of magnitude as T decreases from 100 to 25 mK. For $R_g = 170\ \Omega/\square$, on the other hand, R_0 drops rapidly with decreasing temperature until it reaches a minimum value at approximately 50 mK, below which it rises again. As T tends to zero, R_0 appears to approach a constant value: we measure roughly the same value for $R_0(R_g = 170\ \Omega/\square)$ at both 37 and 25 mK. We cannot rule out sample heating as the cause of this behavior; a sample with a lower R_N would be required to investigate this issue. The quasireentrant

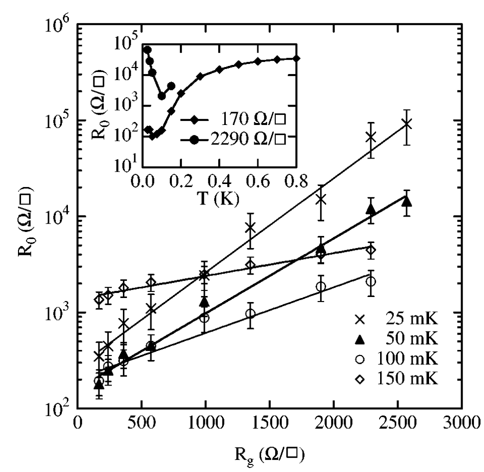

FIG. 3. Zero-bias resistance R_0 of the array versus the resistance per square R_g of the ground plane, for four temperatures. The solid lines are fits to an exponential, as described in the text. The inset shows the temperature dependence of R_0 for $R_g = 170\ \Omega/\square$ and 2290 $\Omega/\square$.

nature of the superconductivity in the present work suggests that our array would not reach a zero-resistance state at $T = 0$ K. Similar quasireentrant behavior has been seen in previous studies of arrays [19] and granular films [1], and is the subject of some debate [20,21].

Finally, although we have reported data from a single array, we have corroborating evidence for the reproducibility of these results. We thermally cycled the array three times, and found that R_N progressively increased, from 21.6 to 22.5 to 23.4 kΩ. Thus, in effect, we made measurements on three somewhat different samples. The small change in R_N produced a major change in the supercurrent, from 9 to 4.5 to 2.5 nA, respectively, at $T = 25$ mK for $R_g = 170\ \Omega/\square$. In each case, R_0 was exponentially dependent on R_g. Furthermore, a similar array grown earlier on a degenerately doped Si substrate (with fixed resistance) also showed enhanced superconductivity, confirming the effect of the ground plane. In fact this prior result motivated the work reported here.

In conclusion, we have presented measurements of the I-V characteristics of a 2D array of superconducting islands linked by Josephson junctions and in close proximity to a 2DEG. We use the 2DEG as a source of variable dissipation for the array by varying its resistance per square R_g via a back-gate voltage V_{BG}. Measurements of the capacitance to ground C_g of the islands indicate it is independent of V_{BG}, so that changing V_{BG} changes only the dissipation and no other relevant physical parameters. As the dissipation is decreased, the I-V characteristics of the array change from superconductorlike with a pronounced supercurrent to insulatorlike with a clear charging gap. Simultaneously the zero-bias resistance increases exponentially with R_g. We interpret these data as evidence for a dissipation-driven S-I transition. Many questions remain unanswered, such as the nature of the coupling between the array and 2DEG, the effect of array dimensionality on the transition, and to what universality class the transition belongs.

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