Field-enhanced superconductivity in disordered wire networks

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The superconducting transition was studied in Al wire networks with built-in positional disorder. Application of small transverse magnetic fields *increased* the mean-field critical temperature in the disordered networks but not in the ordered networks. The magnitude of this T_c enhancement was independent of changes in bias current, probe separation, and measurement configuration, unlike the apparent T_c shifts associated with nonequilibrium resistance anomalies previously observed in superconducting microstructures.
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Superconductivity in mesoscopic or low-dimensional systems has received considerable experimental and theoretical interest in recent years. A rich variety of new phenomena can be observed in mesoscopic superconducting structures when the sample dimensions are comparable to or smaller than the superconducting coherence length.[1–9] For example, striking mesoscopic effects involving quantum interference,[1] critical field,[2] and nonlocal[3,4] or anomalous[5–9] magnetotransport have been observed recently in small superconducting loops and wires.

Superconducting wire networks are ensembles of small loops and thus may exhibit both mesoscopic and macroscopic effects.[10] Similar to Josephson junction arrays (JJA's),[11] they have been used as model systems to study frustration,[10] critical behavior,[12] effects of disorder or fractal geometry,[13–16] and vortex dynamics.[12,14,17] The magnetic-field-dependent critical temperature of periodic networks $T_c(H)$ oscillates with maxima corresponding to rational values of the average number of flux quanta $f=\phi/\phi_0$ in each elementary loop. With the introduction of built-in areal disorder, e.g., by random displacement of wires or nodes, the $T_c(f)$ oscillations are damped out with increasing field in JJA's (Ref. 11) and wire networks.[14] Disorder introduced by removal of bonds rapidly destroys fine structure in the $T_c(H)$, an effect which has been argued to relate to localization of the superconducting wave function.[15]

In this paper we report investigations of $R(T)$ and $T_c(H)$ in positionally disordered superconducting networks. The kind of disorder used is identical to that used in one set of JJA experiments.[11] In a magnetic field, a random flux component appears in each cell, which is anticorrelated in neighboring cells, producing (at integer f) an equivalence to the XY model with random Dzyaloshinskii-Moriya interactions. At high f values, this system can be described as a gauge glass, and was predicted to have a complex vortex dynamics.[17] We observed T_c *enhancement* in small applied fields in the disordered networks, but not ordered networks. The magnitude of this effect is independent of current and measurement configuration. This apparently global effect is distinct from but possibly related to the localized nonequilibrium resistance and T_c anomalies which were previously observed in small Al microstructures.[5–8,3]

The networks studied consisted of square Al wire grids of 200×100 wires, and were fabricated at the Cornell Nanofabrication facility using electron beam lithography and lift-off techniques. The networks had wire widths of 250 nm and average lattice constant (wire spacing) $a=2\ \mu$m. Positional disorder was added to regular square lattices by random displacement of the nodes $\mathbf{r}/a=(n_x+\delta_x, n_y+\delta_y)$ with $n_{x,y}$ integers and $\delta_{x,y}$ a random number uniformly distributed in the range $[-\Delta,\Delta]$ with $\Delta=0$, 0.05, 0.10, 0.15 (see Fig. 1 inset). The Al films were electron beam deposited onto oxidized silicon substrates. All of the networks discussed here were prepared in parallel from the same Al film deposited on a single silicon wafer, while samples fabricated from other wafers produced similar results. The Al film had thickness 30 nm, sheet resistance of $R_{\mathrm{square}}=1.0\ \Omega$ at 4.2 K, and residual resistance ratio $R_{300\ \mathrm{R}}/R_{4.2\ \mathrm{K}}=1.7$. To maximize current uniformity, large Al current contact pads were used, each covering one entire edge of the network. Multiple closely spaced voltage leads were patterned on each side of the network, with a separation of three or ten cells. The voltage leads were 250 nm wide Al which joined at network nodes, and telescoped out to large contact pads.

The measurements were carried out in a liquid ^{3}He cryostat with a base temperature of 300 mK. The cryostat was enclosed in a double μ-metal shield, within a radio-frequency shielded room. Computers and most instrumentation were kept outside of the room and interfaced via filtered lines. Sufficient RF filtering is critical for these kind of measurements.[4] Thus, all electrical leads entering the cryostat were additionally filtered by π filters with a roll-off frequency of 1 Mhz. The transverse magnetic field was produced with a small copper solenoid held at 4.2 K.

The mean-field critical temperature was measured using a four-probe technique with a sinusoidal current bias of typically 1 μA, and lock-in detection. The current dependence was also studied for currents from 20 nA to 10 μA. The mean-field $T_c(H)$ was measured by holding the resistance fixed at half its normal-state value by feeding the sample

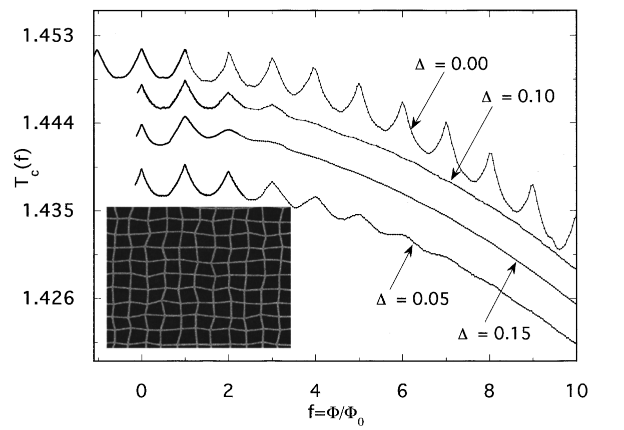

FIG. 1. Superconducting-normal phase boundary, defined by $R/R_n=0.5$, for networks with various disorder strengths Δ. Note that $\phi/\phi_0=1$ corresponds to $H=5$ G. The vertical position of each curve is uncertain to 1%, due to variations in the thermometry after cycling to room temperature. Inset: SEM micrograph of a disordered array with $\Delta=0.15$.

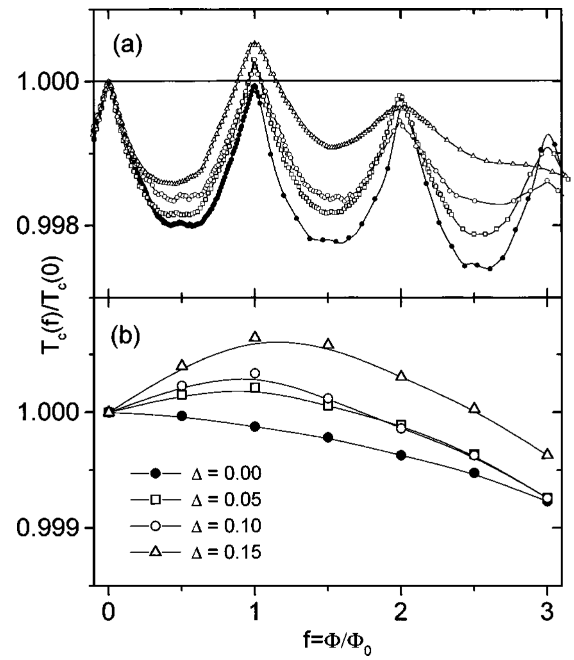

FIG. 2. (a) Normalized T_c vs ϕ/ϕ_0, for various disorder strengths. (b) Midpoints of each oscillation half period of the normalized T_c vs ϕ/ϕ_0 shown in (a).

voltage into an analog temperature controller (LR-130) while the field was slowly swept. The T_c measured in this way decreased with measuring current, as $I^{2/3}$, consistent with mean-field expectations, demonstrating that heating is minimal in the range of interest. Relative shifts of T_c were resolved to better than 0.1 mK.

In Fig. 1 we show the experimentally determined superconducting-normal phase boundary for disordered networks with $\Delta=0$, 0.05, 0.10, 0.15. The small apparent sample to sample shifts in the zero-field value of T_c are related to lack of reproducibility in the thermometry after cycling the temperature. The T_c oscillations decrease with increasing field in the disordered networks as expected.[11,14] All networks also show the expected quadratic background decrease of T_c with field due to the finite wire width. The zero-temperature superconducting coherence length was determined to be 83 nm, based on this quadratic background. The magnitude of this quadratic term decreases slightly with increasing disorder, indicative of the geometric differences and/or slightly smaller linewidths (4%) for the most disordered samples compared with the ordered samples.

Close inspection of the $T_c(H)$ curves, normalized to $T_c(0)$, also reveals a small *increase* in T_c with field at low fields in the disordered networks but not the ordered network [Fig. 2(a)]. The subtle increase appears to be superposed on top of the usual periodic and decreasing components of $T_c(H)$. Figure 2(b) shows the normalized $T_c(H)$ curves with the periodic component removed. This enhancement effect clearly increases with disorder. The effect was not strongly dependent on what fraction of the normal state resistance was used to define T_c, ranging from $R/R_n=0.1$ to 0.9, as seen in Fig. 3. $R(T)$ curves measured under identical conditions for an ordered network exhibit a smaller and opposite shift with field.

The resistive transition was also studied as a function of current over a wide range of current from 20 nA to 10 μA, corresponding to current densities from 3×10^4 to 1.5×10^7 A/m^2. The T_c enhancement at $H=5$ G ($f=1$) relative to the zero-field value, which is designated ΔT_c and indicated with arrows in Fig. 3, was independent of current over this range, as shown in Fig. 4(a). In order to rule out various artifacts which had previously been observed in superconductor measurements,[10,18] the voltage was measured and current was injected with different leads in different locations on the network, and with varying distance between voltage leads. The measured T_c shifts were independent of voltage lead separation for separations ranging from 6 to 140 μm, and independent of whether the voltage leads were on the same or opposite sides of the network, see Fig. 4(b). The effect was also unchanged when current and voltage leads were switched, with current injected into the narrow 0.25 μm leads, as opposed to the wide 200 μm pads. This strongly suggests that the T_c enhancement is a global property of the disordered networks, and not an artifact of the measurement configuration.

Any explanation for T_c enhancement in a field depending exclusively on wire properties, without invoking network ge-

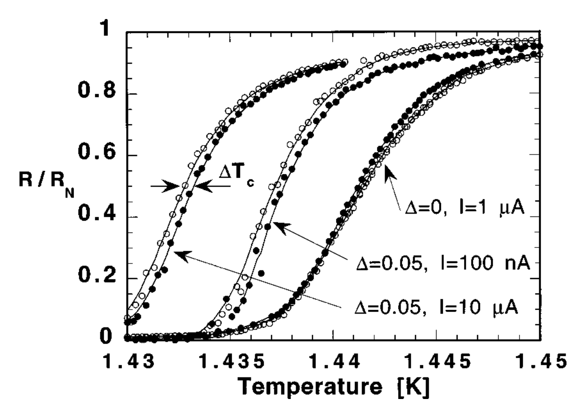

FIG. 3. Resistance vs temperature in the vicinity of the superconducting transition for disordered and regular networks at $\phi/\phi_0=0$ (open symbols) and $\phi/\phi_0=1$ (filled symbols).

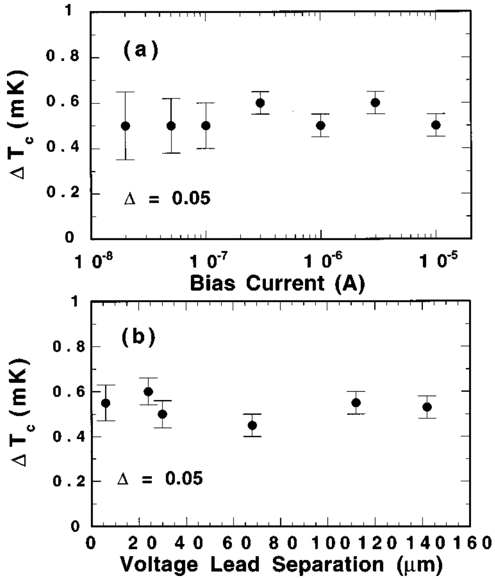

FIG. 4. (a) Critical temperature increase, ΔT_c, for $f=1$ relative to $f=0$ [as illustrated in Fig. 3(a)] vs bias current for a network with $\Delta=0.05$. (b) The ΔT_c vs voltage lead spacing, for the same network.

ometry must be ruled out, since the effect is absent in ordered networks simultaneously prepared from the same film and measured under identical conditions. Earlier studies of wire networks with disordered, fractal, or quasicrystalline patterns, including those with wires intersecting with a range of angles,[11–14] did not report effects such as those we have observed. Although wire networks with the kind of positional disorder discussed here were not previously studied. The networks in most of these earlier studies also had slightly lower sheet resistances and slightly larger coherence lengths. Anomalous $T_c(H)$ were observed in Al oxide wire networks and single wires, when measured with moderate currents, and only at the foot of the resistive transition.[10] This was attributed to proximity effect and quasi particle injection associated with measuring close to a wide contact pad. Since the T_c we observed was independent of the proximity to the wide current pads (up to 190 μm separation), and independent of voltage lead arrangement or spacing, and switching of voltage-current leads, we can rule out these kinds of proximity effects.

What are the effects of disorder that could possibly increase T_c in a field? At $f=1$, where the enhancement effect is near its maximum, the disordered networks will have random screening currents due to the areal disorder of the cells. These would ordinarily only lower T_c. When combined with the transport current, a favorable situation could occur in some cells, raising T_c. However, this effect would vary from cell to cell and should average away in many cells. By using different voltage leads, we sampled different sections of the network (down to three cells), within which the disorder is different in detail. No significant differences in the enhancement effect were observed [Fig. 4(b)]. In addition, the independence of the effect on transport current over a wide range is not consistent with a balancing of screening and transport currents.

Apparent T_c enhancements with field were reported earlier in short, narrow Al microstructures (wires[5] and loops[6]), and were attributed to nonequilibrium resistance anomalies.[5–8,3] These anomalies appeared as narrow peaks in resistance high on the $R(T)$ transition curve, in some cases exceeding the normal state resistance. At high current densities, the peak anomalies broadened down the resistive transition, producing an apparent reduction in T_c. Small magnetic fields quenched the anomalies, producing an apparent enhancement in T_c. These T_c enhancements vanished altogether at low current densities of $<6\times10^6$ A/m^2,[6] over two orders of magnitude larger than our lowest current densities. The resistance anomalies are observed when superconducting voltage leads probe *nonequilibrium* charge imbalances within a quasiparticle relaxation length λ_Q of a superconducting-normal interface (SNI). Such interfaces may be produced at nodes where current carrying leads intersect with wires carrying no current,[5] in samples with heterogeneous superconducting properties,[8] or at rf-noise-induced phase-slip centers (PSC's).[4] These anomalous effects are *local* in that they diminish rapidly when voltage lead spacings are larger than λ_Q, which is typically about 10 μm at these temperatures.[5]

In fact, resistance anomalies similar to but smaller than those previously observed[5–8,3] could be detected in our disordered networks. The effect can be seen in the middle curves of Fig. 3 as a slight rise in resistance, very high on the transition in zero field. The amplitude and shape of these anomalies was strongly dependent on voltage lead spacing (sample size), current (as seen in Fig. 3), and rf noise,[4] consistent with the earlier results on single wires and loops.[5–8,3] This behavior contrasts sharply with that of the T_c enhancement effect in the networks, which exhibited little current or lead spacing dependence.

The observation of resistance anomalies only in the disordered networks provides a possible clue to the origin of the T_c enhancement effect. Enhanced superconductivity at network nodes in the presence of transport current,[19] makes it probable that SNI's occur in some temperature range in both kinds of networks. The symmetric occurrence of SNI's around voltage leads in ordered networks may nullify anomalous resistance effects. Inhomogeneous current flow, or possible localization effects[15,16] may make disordered networks more susceptible to SNI occurrence or make their positions more random. SNI's are also produced at PSC's, which were shown to occur *collectively* in an entire row of cells across a regular wire network.[10]

We could assume that SNI's and resultant anomalies occur at a distribution of temperatures in a disordered network, giving a shift of the entire $R(T)$ curve to lower temperature. In a magnetic field, the T_c at nodes will be suppressed more strongly than the T_c of links, due to the increased wire width. This would tend to reduce amplitude fluctuations, leading to a quenching of SNI, the resistance anomalies, and the apparent decrease in T_c. Alternatively, the fact that λ_Q decreases with field may be most important.[5] At higher currents, each anomaly is broadened but their summed effect on the $R(T)$ curve could remain about the same. This could account for the independence of the T_c enhancement on current. The invariance with lead spacing remains an important point to be explained in this scenario. This may require theoretical analysis of transport through a random collection of SNI's or PSC's (Ref. 8) in a two dimensional network.[10]

To summarize, we have observed field enhanced critical temperature in disordered superconducting networks. This effect was observed to be independent of voltage lead spacing and current, and increased with disorder in the networks. Various possible extrinsic origins and simple mechanisms were ruled out and mechanisms involving superconducting-normal-interfaces were discussed. Various other effects may need to be considered, such as Andreev reflection at the SNI.[20] A negative Josephson coupling between localized superconducting regions was recently invoked to explain negative magnetoresistance in narrow Pb wires near the superconductor-insulator-transition (SIT).[9] In disordered networks, amplitude fluctuations near T_c would be analogous to those near the SIT, suggestive of a possible connection.

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