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.

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.\(^1\) For example, striking mesoscopic effects involving quantum interference,\(^2\) critical field,\(^3\) and nonlocal\(^4\) 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.\(^17\) 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.\(^3\)–\(^8\),\(^3\)

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) \( a = 2 \mu \text{m} \). 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 \( R_{\text{square}} = 1.0 \text{\,}\Omega \) at 4.2 K, and residual resistance ratio \( R_{300 \text{K}}/R_{4.2 \text{K}} = 1.7 \). 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 \( \mu \)-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 \( \pi \) 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 \( \mu \text{A} \), and lock-in detection. The current dependence was also studied for currents from 20 nA to 10 \( \mu \text{A} \). The mean-field \( T_c(H) \) was measured by holding the resistance fixed at half its normal-state value by feeding the sample...
The field was slowly swept. The sample to sample shifts in the zero-field value of $T_c$ for disordered net-works with superconducting-normal phase boundary for disordered nets were determined to be better than 0.1 mK. The magnitude of this quadratic term decreases slightly with increasing disorder, indicative of the geometric differences 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. 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 disor-dered 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 \(\mu\)A, corresponding to current densities from $3 \times 10^4$ to 1.5 $\times 10^7$ A/m$^2$. The $T_c$ enhancement at $H = 5$ G ($f = 1$) relative to the zero-field value, which is designated $\Delta T_c$ and indi-cated 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 supercon-ductor measurements, 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 \(\mu\)m, 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 \(\mu\)m leads, as opposed to the wide 200 \(\mu\)m 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-
omentry 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, 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. This was attributed to proximity effect and quasi particle injection associated with measuring close to a wide contact pad. Since the $T_c$ observed was independent of the proximity to the wide current pads (up to $190 \mu m$ 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 $T_c$, but in an entire row of 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 and loops), and were attributed to nonequilibrium resistance anomalies. 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 $<6 \times 10^6 \text{A/m}^2$ 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 $\lambda_Q$ of a superconducting-normal interface (SNI). Such interfaces may be produced at nodes where current carrying leads intersect with wires carrying no current, in samples with heterogeneous superconducting properties, or at rf-noise-induced phase-slip centers (PSC’s). These anomalous effects are local in that they diminish rapidly when voltage lead spacings are larger than $\lambda_Q$, which is typically about 10 $\mu m$ at these temperatures.

In fact, resistance anomalies similar to but smaller than those previously observed 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, consistent with the earlier results on single wires and loops. 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, 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 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.

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 $\lambda_Q$ decreases with field may be most important. 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.
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. 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). 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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10 See, e.g., M. Giroud, O. Buisson, Y. Y. Wang, B. Pannetier, and D. Mailly, J. Low Temp. Phys. 87, 683 (1992), and numerous references therein.
15 C. M. Soukoulis, Gary S. Grest, and Qiming Li, Phys. Rev. B 38, 12 000 (1988); F. Yu, A. M. Goldman, R. Bojko, C. M. Soukoulis, Qiming Li, and Gary S. Grest, ibid. 42, 10 536 (1990); Gary S. Grest (private communication).