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Fabrication of 3D proximity coupled Josephson junction arrays

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Experimentally realizable 3D arrays of Josephson junctions have been a goal of researchers since 2D Josephson junctions (JJ) arrays were first introduced. In the past, it has proven to be technically impossible to manufacture 3D proximity-coupled arrays. Recent advancements in etching technology have now made fabrication more feasible. In this paper, we present details of our fabrication process.

In 1981, two-dimensional (2D) arrays of Josephson junctions (JJ) were first introduced as a model system in which to study the physics of random, weakly coupled granular thin film supercondutors [1]. These arrays usually consist of 'islands' of superconducting material arranged in a 2D lattice sitting on a normal metal underlayer. Adjacent islands are Josephson coupled via the proximity effect creating a 2D network of junctions. In over a decade of intense study by many groups worldwide, 2D JJ arrays have taken on a legitimacy of their own as something more than just a simple model system. They are now utilized as voltage sources and as voltage standards by the National Institute of Standards and Technology (NIST); they are used by the defence industry as bolometers and very sensitive switches; and they are extremely sensitive to very small magnetic fields and so offer uses in magnetic field detection. In addition, they offer a chance to study many phenomena (e.g. Giant Shapiro steps) that do not occur in the original granular superconductors they were meant to model.

The natural extension of the 2D JJ array is a 3D JJ array, and there is every indication that these arrays would follow the same course as 2D arrays and become an important model system for a variety of physical theories. Realization of a 3D array would allow us access to a whole palette of experimental investigations. For instance, we would be able to do 'statistical mechanics on a chip', measuring a variety of critical exponents for comparison with mean-field, percolation, and other theories [2]. We would also be able to measure regimes where ordinary mean-field theories fail. We could experimentally create 'magnetic' spin systems that can be frustrated in three dimensions and probe their electrical properties [3]. We would be able to investigate the 3D superconducting phase transition, the details of which are inaccessible in ordinary bulk superconductors as the transition width is only micro Kelvins wide [4]; JJ arrays, because they are weakly coupled systems, have very wide transitions, often several degrees wide. The transition may also depend on the nature and degree of the coupling between superconducting islands in the x, y, and z directions. These arrays provide

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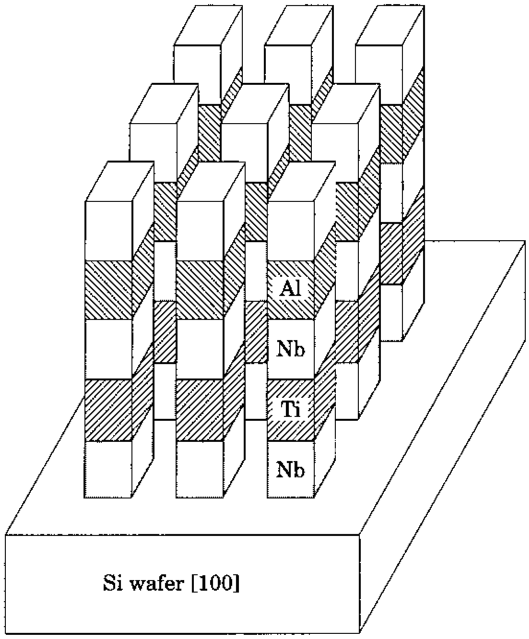

Fig. 1. Schematic diagram showing the columns of alternating superconductor/normal metal cubes after etching. Top cubes represent residual e-beam resist.

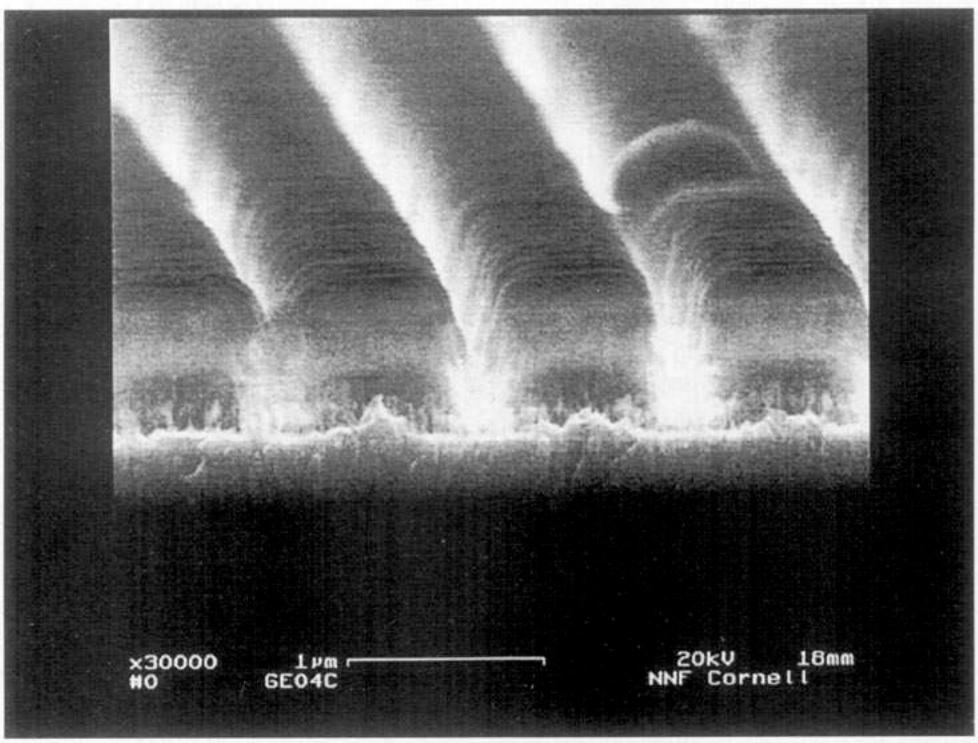

Fig. 2. Electron micrograph of a three-layer sample after etching. Sample is viewed from the side to illustrate vertical sidewall etching. Features shown are 0.5 μm squares with 0.5 μm gap spacing.

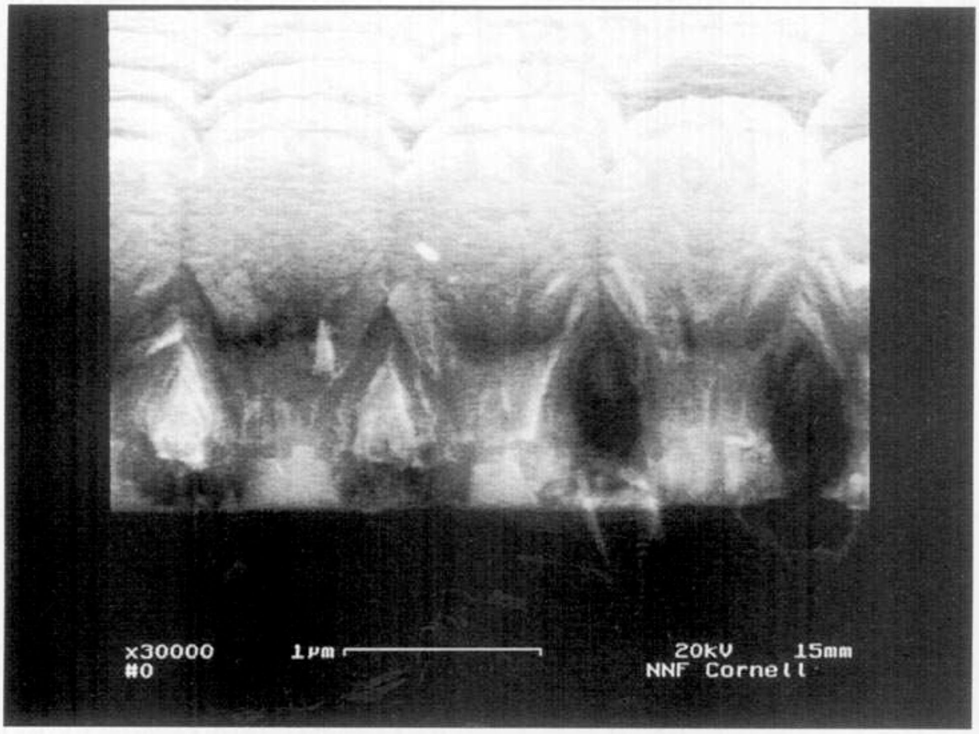

Fig. 3. Electron micrograph showing side view of a sample with similar features as in Fig. 2 after backfilling with 600 nm of Ti metal.

an excellent vehicle to investigate the role of intralayer and interlayer coupling on the mechanism of the superconducting transition. As such, they provide an ideal model system to explore the superconducting mechanism and flux motion in high temperature oxide superconductors [5].

Ideas for creating 3D JJ arrays were proposed shortly after 2D arrays were introduced, but for many years implementation proved technically impossible. Recent advances in reactive ion etching and deposition technology [6] have now made the fabrication of 3D arrays feasible. In this paper, we report on our method for fabricating these arrays and recent progress that we've made toward achieving our goal.

An overview of our 3D fabrication process is as follows. We begin by depositing on to an oxidized silicon wafer alternating layers of superconducting (Nb) and normal metal (Ti) films until the desired number of layers is achieved; each layer is 300–500 nm thick. The first and final layers are superconducting, so in principle, the number of layers ranges from three to N where N is odd. In practice, the maximum number of layers is likely to be limited to approximately nine or 11 because very thick multilayer films have considerable internal stress due to lattice mismatches and have a tendency to peel off the substrate. Our current studies have focused on three- and five-layer films.

In the second step we pattern using electron-beam lithography an Al etch mask on to the top layer. The etch mask consists of a square lattice of squares, of a size nearly identical to the individual layer thickness in the multilayer films, with a gap of the same size separating adjacent squares. The exact dimensions of the squares, and the spacing between squares, depend upon both the degree of anisotropy and the nearest-neighbor coupling strength desired. The ability to control the anisotropy offers the opportunity to model many other systems, including high T_c superconductors. We have focused on two sample geometries: 0.5 μm squares with 0.5 μm gap spacings and 1.0 μm squares with 0.9 μm gap spacing.

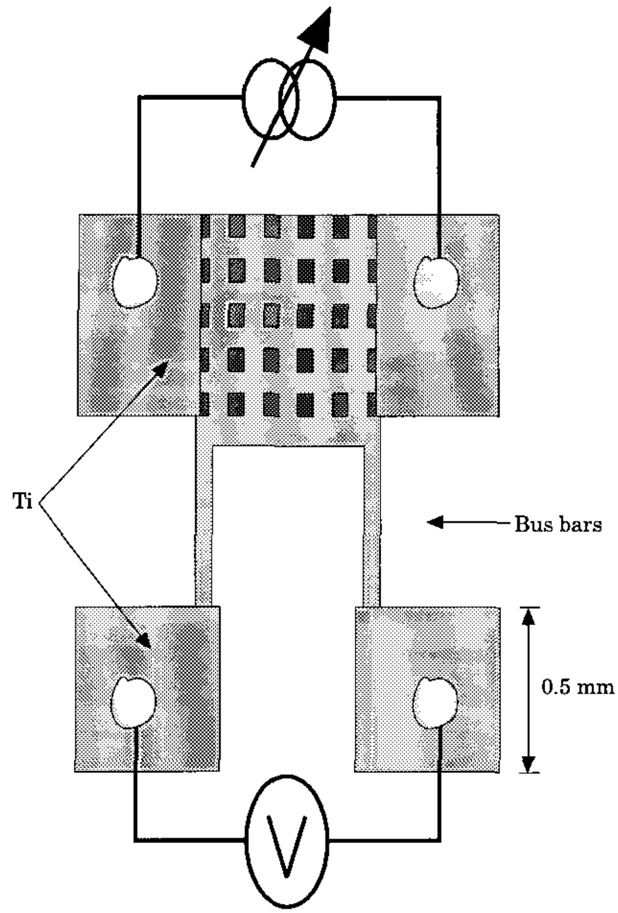

Fig. 4. Schematic diagram of the array voltage and current contact pad arrangement.

The patterned multilayer film is then directionally etched such that the material between the squares is removed, leaving behind a 'forest' of free standing square columns, each consisting of alternating cubes of superconductor and normal metal (see Fig. 1). Most etching techniques (e.g. reactive ion etching) are non-directional or, at best, marginally directional so that etching micron deep features into a metal film often results in undercutting the mask and destruction or blurring of the pattern. Recent advances in plasma-etch technology, specifically the introduction of electron-cyclotron resonance (ECR) etching, allow us to control more precisely the etching directionality, enabling us to etch more than a micron deep into our multilayer films with nearly vertical sidewalls. Figure 2 shows an electron micrograph of a sample after etching. The sample has been cleaved and is viewed from the side to examine the sidewall profile, which is nearly vertical. This sample consists of three layers (Nb-Ti-Nb), each 300 nm thick, and an Al etch mask (thin bright layer on top) approximately 200 nm thick, so that the trenches are approximately 1 μm in depth. This particular sample shows 0.5 μm squares with 0.5 μm gaps.

Similar but somewhat less successful results have been achieved for five-layer films. Here, the etching becomes complicated by several factors, such as loading—as the aspect ratio increases, it becomes more difficult to get the etchant into the trench and get the etched material out so that the etching process slows considerably and becomes much less directional. As a result, mask erosion becomes a problem and feature definition degrades. Etching studies on the five layer films are ongoing.

Once the columns are successfully etched, the trenches between the columns are backfilled by normal metal (Ti) evaporation. Point source evaporation is known to be highly directional and has proven to be useful in backfilling the etched samples. Figure 3 shows an electron micrograph of a sample after backfilling. This sample has the same nominal geometry as the one shown in Fig. 2: a three-layer film with 0.5 μm squares with 0.5 μm gap spacing. Though the trenches were on the order of 1 μm in depth, only 600 nm of Ti metal was evaporated on to the sample. Our concern here was that complete filling occurred between adjacent squares and that the number of voids was kept to a minimum. As can be seen from Fig. 3, our evaporation technique proved to be largely successful in backfilling the trenches.

The final step involves patterning the sample current and voltage contact lead geometry using conventional contact lithography (see Fig. 4). The excess Ti metal is then etched away leaving the backfilled array and contact geometry behind.

In summary, we have successfully etched and backfilled three-layer samples in our 3D array geometry. We should have working 3D arrays of size $N \times N \times 2$ superconducting cubes (where N is the number of Nb cubes in the xy plane), in the very near future. Work continues on five-layer samples (i.e. $N \times N \times 3$).

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