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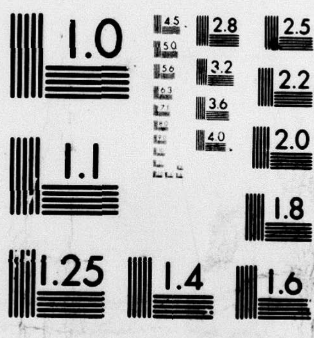

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SUPERCONDUCTING WEAK LINKS FOR MIXING AT MILLIMETER-WAVE FREQUENCIES

FINAL REPORT

T. Van Duzer

15 May 1973 - 30 September 1979

U. S. ARMY RESEARCH OFFICE

DAAG29-76-G-0191
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ELECTRONICS RESEARCH LABORATORY
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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study is made for application of Josephson devices for millimeter-wave mixing. Technology for fabrication of small area silicon-coupled sandwich-type Josephson junctions is developed. A thin strip of superconducting metal film deposited on a degenerately doped silicon surface with a 0.1 - 0.3 μm gap cut across the film is shown to constitute a Josephson junction with certain significant advantages. A design of a Josephson junction two-dimensional array is made its properties are

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studied theoretically. A model for calculation of the action of a developer on a resist is devised. Calculations of the effect of thinning a substrate on the exposure of electron resists are made.

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SUPERCONDUCTING WEAK LINKS FOR MIXING AT MILLIMETER-WAVE FREQUENCIES

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The goal of this work was to study the use of superconducting weak links to achieve more sensitive millimeter-wave mixing. The work has emphasized fabrication technology for some types of structures that show considerable promise for having very desirable electrical and mechanical properties. In pursuing device fabrication technology, we continued work conducted during the previous grant period on exposure of a resist by an electron beam; that was brought to an even more useful state by developing a method of simulating the action of a developer on the exposed resist. We have studied arrays of Josephson junctions both with respect to their dc properties and their application for detection of electromagnetic waves.

JOSEPHSON JUNCTIONS WITH COUPLING THROUGH A SILICON MEMBRANE

The device on which we have concentrated most of our efforts is one in which the coupling between two superconducting thin films is through a crystalline silicon layer on the order of 500 Å thick. This structure, developed earlier under other sponsorship, is of sandwich form and has the potential of being made with rugged superconductive materials such as niobium and its alloys and compounds, which also have high transition temperatures. The latter fact makes them candidates for detection and mixing applications in which operation is possible at temperatures attainable with small, light-weight refrigerators. Our efforts were directed toward making small-area junctions to obtain impedance levels suitable for optimum matching to waveguide systems. The formation of the silicon structure is by the use of a selective etchant and is done in two major steps. First a deep boron diffusion is made in such a way that the doping concentration at ≈ 3 μm from the top surface is 7×10^{19} cm^{-1}. Etching is done through an SiO_2 mask on the other side using ethyelne-diamine-water-pyrocatechol. This etchant works rapidly in the ⟨100⟩ directions and very slowly in the ⟨111⟩ directions leading to an etch pit with {111} planes as walls. The etching action is stopped where the concentration of boron reaches 7×10^{19} cm^{-1}. After out-diffusing the dopant and measuring the thickness of the roof of the etch pit, we proceed to a second etch step. A shallow diffusion is done on the lower side of the roof and an etch pit is made from the top side. The result is to be a pit with a floor of 500 Å thickness and area of 1 μm^2.

We designed an electrode system for the chip containing the junction, which allows near-optimum matching. The design junction impedance is 40 ohms. The entire bottom of the chip is coated with a superconductor. On the top, the electrode is shaped to form a microstrip with the lower superconductor. The width of the microstrip electrode is designed to give a 40 ohm characteristic impedance in each of the two different thickness regions and is tapered uniformly in-between. Thus, the electrode width is 0.26 mm on the main body of the 0.24 mm thick chip; over the roof of the large etch pit which is 2.6 μm thick, the electrode width is 2.9 μm. A linear taper is used to join the two regions. Modeling could be done at lower frequencies to adjust the shape of the connection region, but that refinement is not yet justified.

The out-diffusion step has led to some difficulties in that a spurious etching of the wafer surface has occurred. Considerable effort has been expended on determining the causes and possible solutions. One approach has been to avoid that step by using timing rather than boron doping to stop the first etch step. This procedure leads to a greater variety of thicknesses of the roofs of the large etch pits than does the boron-stopped etching. We measure the thicknesses of the roofs on the large etch pits by measuring the energy required by an electron beam to pass through the membrane. Data exist in the literature which relate energy to thickness and we have checked it by measuring the edge thicknesses of broken membranes which are also measured by electron transmission. The thickness information is needed for masking the second etch step to get the required junction size. One useful aspect of this approach is that it avoids the damage caused by heavy doping dosage for the first etch step. We have not yet evaluated the effect of reducing the damage.

Some good devices have been made but not yet with sufficiently controllable properties. This work is continuing with other DOD support since, despite the difficult fabrication procedures that are required, the desirable electrical and mechanical properties justify the effort.

COPLANAR SILICON-COUPLED JOSEPHSON JUNCTIONS

This device embodies an extension of the concept underlying the sandwich structure discussed above. The fabrication is simpler and has more potentiality for large arrays. A narrow (say, 20 μm) line of a superconductor is deposited on a highly doped surface of a silicon wafer. Then, using electron-beam lithography and sputter etching, a narrow gap (on the order of 0.1-0.3 μm) is cut across the strip. The two halves of the strip are then the two electrodes and they are weakly coupled through the highly doped (degenerate) silicon. The critical points are that the surface of the silicon be free of oxide and contaminants, there be good adhesion of the superconductor to the silicon, and that the gap be cut cleanly, with no residue of the superconductor in the gap. So far, we have demonstrated that the device works and have seen both hysteretic and nonhysteretic I-V characteristics. We have recently done an experiment to ensure that the electrical coupling is not through unobservable (with a scanning electron microscope) residue of the superconductor. A checkerboard pattern of doped and undoped regions is formed and one device is made on each square. In this way all devices are closely spaced so they receive essentially the same processing. None of the devices on the undoped regions had electrical coupling and ones on the highly doped surface did. We take this to be a confirmation that the devices worked by coupling through the highly doped silicon.

Assuming that etching techniques can be worked out, this device should be adaptable to use with rugged superconductors such as niobium and its alloys and compounds. It could, therefore, be used at temperatures accessible to miniature refrigerators. The devices are presently being made with lead-indium alloy electrodes which are resistant to corrosion but are easily scratched unless protected with an insulating overlay.

ARRAYS OF JOSEPHSON JUNCTIONS FOR DETECTION AND MIXING

As a preliminary effort to the RF study of arrys, we analyzed the dc properties of simple arrays of two or three junctions connected in parallel in superconductive loops. We studied the dependence of the maximum zero-voltage current on magnetic field and the dependence of that on the functional form of the relation between the current through a Josephson junction and the electron-pair phase difference across it.

We have made the theoretical study of the use of arrays for detection and mixing of millimeter waves. The structure of interest would be a square chip containing parallel thin-film strips of superconductor broken by Josephson junctions at a number of places. The surface impedance is designed to be equal to the wave impedance of plane waves, 377 ohms.

The design requirements were worked out assuming the use of the bismuth-coupled Josephson junctions reported by Ohta. The principal advantage of the array is that it has a large effective area. We also designed an array to test in a waveguide. Quantitative measurements are easier to make accurately in waveguide systems than in the quasi-optical system intended for $0.5 \text{ mm} < \lambda < 1.0 \text{ mm}$ so it would be preferable to test the basic ideas of arrays in such a system at a lower frequency. The waveguide array could also have an advantage for applications over single junctions of being matched over a broader band of frequencies. The array is designed to cover an entire cross-section of the waveguide; for ideal matching, it should have an effective surface impedance equal to the wave impedance of the TE_{10} waveguide mode at the design frequency. It would be ideally matched at only one frequency but the mismatch at other frequencies would be small compared with that encountered when matching to single junctions in cavity arrangements.

EXPOSURE AND DEVELOPMENT OF ELECTRON RESIST

In the preceding grant period, we developed a theoretical model that described the exposure of resists by electron beams. This work was continued in order to apply the model to the study of some important special cases. One case was the effect of using a thin substrate to reduce the electron backscattering. It was found that profound effects are obtained if the substrate thickness is reduced to the range 0.4 μm or less. The calculations showed that it should be possible to fabricate parallel arrays of thin-film lines with 0.075 μm center-to-center spacing and 0.1 μm thickness. We also studied exposure at the edges of large regions. These included straight edges as well as inside and outside right-angle corners. The work suggested that the charge deposited during exposure should be programmed in order to get the right kind of exposure for different shapes. This problem of exposure of nearby regions as a result of backscattering from the substrate has come to be known as "proximity effect."

The above work assumed that the action of a developer would stop at a contour of equal energy absorption, which is a reasonable approximation for some resist and developer combinations. More accurate calculations of the effect of developers were made subsequently. In the work on this grant, we used a model which consisted of a string of compuational points lying perpendicular to the exposed line. The string is initially along the top surface of the resist. Each computational point on the string is advanced into the resist by an amount that depends on the exposure there and the known relation between etch rate and exposure for that resist. As time proceeds, the string of points moves into the resist, distorting according to the local etch rate, and representing the actual front of developer action. The computational procedures included methods for adding and deleting points along the string as the distortions change the point spacing. This analysis was done in collaboration with another group (Professor A.R. Neureuther) and included a comparison with two other methods of calculation. This string method has been included in a program package now being adopted by industry.

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