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This research involved the study of quantized flux lines or vortices in long Josephson junction structures and in superconductive films in the context of electronic device possibilities suggested by these structures. The work encompassed fabrication and low frequency electrical measurement of thin film device configuration coupled with physical device modeling. This was followed by high frequency parameter measurement and creation of circuit models for the devices. In some cases these circuit models were used to model and optimize specific circuits such as amplifiers or oscillators and, when warranted, prototypes were frabicated and tested. The primary structures studied were the long Josephson junction transistors, including the vortex flow transistor (VFT) and the superCIT. In addition, initial success with an exploratory device using a single high Tc superconducting film, the SFFT, led to some concentration on circuit realizations with this device. Comparisons were made of these three devices which were fabricated using a variety of thin film superconductors.

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VORTICES IN LONG JOSEPHSON JUNCTIONS

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SUMMARY

This research involved the study of quantized flux lines or vortices in long Josephson junction structures and in superconductive films in the context of electronic device possibilities suggested by these structures. The work encompassed fabrication and low frequency electrical measurement of thin film device configurations coupled with physical device modelling. This was followed by high frequency parameter measurement and creation of circuit models for the devices. In some cases these circuit models were used to model and optimize specific circuits such as amplifiers or oscillators and, when warranted, prototypes were fabricated and tested. The primary structures studied were the long Josephson junction transistors, including the vortex flow transistor (VFT) and the superCIT. In addition, initial success with an exploratory device using a single high T_c superconducting film, the SFFT, led to some concentration on circuit realizations with this device. Comparisons were made of these three devices which were fabricated using a variety of thin film superconductors.

RESEARCH OBJECTIVES

The research described here involved a study of electronic devices made possible by the various phenomena associated with quantized magnetic flux lines (or current vortices) which are present in thin film Josephson tunnel junctions which have one dimension larger than the so called Josephson penetration depth, and which are also present in somewhat different form in type II superconducting films under an applied magnetic field larger than the lower critical field. The work was an outgrowth of original studies on the potential for high frequency use of a three terminal amplifying device called the vortex flow transistor or VFT. This device consists of a long Josephson junction with an external current carrying control line which provides the magnetic field.

In the grant proposal we cited the following challenges: (1) How can we better understand and control certain aspects of the vortex flow transistor which limit its eventual use as an amplifier? These aspects include a saturation of the small signal transresistance when coupling capacitance is minimized and a tendency to exhibit noisy minor current spikes along with the main flux flow step. These spikes are not always observed, but their existence is a significant problem impeding the achievement of a practical amplifier. (2) How can we construct and test a distributed amplifier structure at high frequencies? The challenges involved in accomplishing this goal include the refinement of microwave coupling circuits to our films and refinement of our fabrication techniques. (3) Which of a group of new device ideas show enough promise, in either furthering our understanding of vortex dynamics or providing a useful electronic function, to be pursued experimentally? (4) Is it possible to incorporate the oxide superconductors into this study in a useful and meaningful way?

We proposed to address these questions through a group of studies. These involved more work than could be performed by students supported by the grant. The last two or three were to be pursued only if sufficient extra funding, such as graduate student fellowships became available. The studies are briefly summarized below.

1. VFT characterization, variable penetration depth, kinetic inductance.

If one treats fluxons as particles, the VFT characteristics and circuit behavior are relatively easy to understand qualitatively. From this point of view, the amplifier becomes an ordinary three terminal device with mechanisms similar to those seen in other common devices such as the field effect transistor, the bipolar transistor and the vacuum triode. The treatment of fluxons as particles introduces one to a number of interesting problems which will probably impact on the semiconductor world when semiconductor devices become small enough. The size of the fluxon can be a significant fraction of the size of the device. A junction containing fewer than 100 fluxons starts to exhibit a grainy behavior which may have significant effect on noise properties. Another important feature is that the loss can be controlled such that the fluxon exhibits ballistic transport rather than the viscous transport usually seen in solid state devices. This makes it possible, for example, to change from a behavior similar to that of a field effect transistor to that of a vacuum tube simply by changing the leakage current of the junction. We proposed to continue a simulation and experimental study of this structure and to ascertain causes for observed behavior which are not obvious from this particle model in order to find limits to its applicability. Two phenomena of interest were the existence of multiple fine step behavior in the volt-ampere characteristic and geometry dependent nonlinearities in the transresistance. It was proposed to continue efforts on a NbN junction technology to enable making devices with position variable penetration depth and with large kinetic inductance which might be used to enhance the transresistance.

2. Study of other devices for distributed amplifiers.

From our first two years of study of the vortex flow transistor, we concluded that the concept of the distributed amplifier is quite important to allow eventual use of the VFT mechanisms for amplification at high frequencies. Such a configuration does two things. It allows for much larger power handling capability than can be provided by a single device. Secondly, it allows incorporation of this very low impedance device into a structure for which a much larger range of impedance levels is possible. Initial studies on a nonhysteretic long junction device, the superCIT, indicated that it might be more suitable for a distributed amplifier configuration than the VFT. Consequently, we proposed to study this more carefully.

3. NbN trilayer technology & a demonstration distributed amplifier.

For a number of reasons, including those cited above, we proposed to augment our existing Nb capability with a NbN-MgO-NbN trilayer technology. We have a fairly unique deposition system which allows us to incorporate ion beam deposition and energization of a growing film with reactive magnetron sputtering. We proposed to study the characteristics of devices and control over their characteristics using this system in conjunction with in-situ stress measurements of the growing films.

The building of a demonstration amplifier was a major goal of this research. This depended, however on the achievement of a reliable fabrication technology as well as a trustworthy high frequency equivalent circuit for the VFT.

4. Study of vortex flow in oxide superconductors, contacts with NbN

At the time of the proposal, we had started to make thin films of the oxide superconductors. We proposed to investigate boundaries between such films and NbN and to look for long junction behavior in grain boundaries. Both investigations were intended to aid in a search for active and passive device applications of these materials.

5. Study of new vortex flow device concepts: non-junction devices, klystron.

It was proposed to continue some exploratory work on the use of Abrikosov vortex flow in films to make amplifying devices similar to the VFT. This had been started with Nb films with the idea of extending the investigation to high T_c materials. It was also proposed to investigate the characteristics of a junction flux flow device coupled to a transmission line resonator. This device is thought to have characteristics similar to a klystron vacuum tube. It would not be transit time limited in speed like the VFT.

RESEARCH ACCOMPLISHMENTS

The following is a summary of results achieved during this study by the principal investigators and their students. Some of the students were supported by the grant and some had other support such as fellowships. The research accomplishments for the first two years of this grant have been discussed somewhat more fully in two previous yearly reports. Detailed accounts of the research done under this grant can be found in the publications and theses cited below.

A. Vortex Flow Transistor Characterization

Work on the vortex flow transistor mechanisms and the effect of kinetic inductance on gain of this device was carried out by Jin-Shyong Jan[1]. He measured the static characteristics of a set of all NbN VFT's which he fabricated with different control line configurations. He saw significant modification to the transresistance due to kinetic inductance in accordance with theory. This has profound effect in increasing the possible gain of directly coupled devices where the control line is electrically connected to the output line. On the other hand, for magnetically coupled control lines, the effect is detrimental. This latter configuration is essential for presently conceived distributed amplifier structures.

The existence of a fine structure of discontinuities in the volt-ampere characteristics was observed often in Jan's measurements. He also identified a second set of current steps on his devices which were subsequently analyzed by graduate student James Thompson[2]. Both the fine structure and the larger steps are due to reflections of electromagnetic energy off junction boundaries. The second set of steps, which are due to generation of antifluxons at one boundary, can be used to design devices with larger transresistance values than originally conceived of. However, since both of these phenomena are due to multiple reflections, any use as part of a device mechanism would cause the transit time cutoff frequency if this device to be lowered. If one wishes to suppress these structures, the most obvious method is to build physically longer devices. This again adversely affects the cutoff frequency of the device.

Thompson carefully studied the effects of junction boundaries by comparing simulation and analysis with measured characteristics of Nb-NbOx-Pb structures. His conclusions concerning the fine steps are very important to potential high frequency use of the VFT. He showed that, with conventional boundaries, the VFT is not a viable amplifying device at high microwave and millimeter wave frequencies because of the large voltage quantization due to these reflections. However, he also showed that the existence of such resonances is not fundamental to device operation and that they can be defeated in principle by such means as terminating the junction in its characteristic impedance, adding parallel resistance to lower the Q of the oscillations, or by adding some other type of structure to defeat the resonance condition[2,3].

B. Modified Devices and the Distributed Amplifier using Nb Technology

Graduate student Mohan Ketkar worked on various circuit and fabrication problems associated with the distributed amplifier concept using superconductive devices. Characterization of the VFT showed that the feed-thru capacitance from control line to junction output is large enough to cause severe limitations to VFT use in distributed amplifier arrays. The capacitance can be reduced through device geometry changes, however as capacitance is reduced so is transresistance. Alternatives were studied because of this limitation. One approach suggested earlier is to use the modified Super-CIT instead of the VFT for this application. The Super-CIT can be approximately modelled as a current controlled current source and hence its current generators can be connected in parallel across the output line. For such a connection the current source for each device can be grounded thus eliminating much of the detrimental effect of the feed-thru capacitance seen with VFT voltage generators which must necessarily be connected in series. Also, the unwanted fine structure seen in the VFT is not evident in the superCIT characteristic. Consequently a Nb based fabrication process for modified Super CIT's was devised in anticipation of incorporating them in the distributed amplifier.

Another aspect of Thompson's work was a theoretical comparison of the amplifying properties of the VFT and the superCIT[2,4]. The conclusions from this study indicate that, except for the advantage of a nonhysteretic volt-ampere characteristic, the super CIT is basically inferior to the VFT. It has about the same maximum transresistance with a higher output resistance. This output resistance is extremely voltage dependent and the device has a very small useable voltage range. Consequently, we did not pursue the fabrication of an amplifier using this device

A preliminary study was made by Ketkar of a second approach for overcoming feed-thru capacitance by use of a balanced device with push-pull excitation[5]. The equivalent circuit of such a device consists of a pair of VFT's in series driven by a balanced control line. The RF currents through the feed-thru capacitors, being in opposite directions, form a loop current to ground. It thus provides high isolation of feed-thru current from the load. A computer simulation of this configuration shows an improvement of more than 60 dB over a single device up to the transit time cutoff frequency which is encouraging. A BALUN is necessary to drive the device however, which complicates the distributed amplifier design. Simulations on a distributed amplifier using balanced VFT's show an improvement in gain up to 100GHz compared with the same structure using single VFT's. Experimentally we have made large series arrays of long junctions but a high frequency distributed amplifier realization awaits a practical solution to the resonance problem in the VFT.

C. Niobium Nitride Trilayer Technology

Graduate student Dave Dawson Elli worked on the basic NbN trilayer. This involved reactive NbN sputtering and ion beam deposition of MgO. He developed a hollow cathode assisted magnetron sputtering technique[6] and also set up an optical in-situ stress measurement to try to find out the effects of film stress on the Josephson junction characteristics[7]. He has observed unusual film growth behavior with this apparatus, including a regime which exhibits a change from compressive to tensile stress during growth. He has also experimented with an AlN trilayer process. Cross-sectional transmission electron micrographs of the trilayers show very sharp spatial transitions, but to date the junction quality has not approached that of good MgO barrier devices. This work, which is not yet completed, is intended to further our understanding of non-ideal volt-ampere characteristics normally seen in NbN junctions. Its main features include the use of different barrier materials, in-situ stress measurements and a transmission electron microscope cross section study of finished devices.

D. Single Layer Flux Flow Devices Using HTS

A fellowship student Jon Martens accomplished some very interesting device and circuit realizations with HTS films[8,9]. Using primarily TlCaBaCuO films supplied by Sandia Laboratories, but also some YBaCuO films from Hypres and BiSrCaCuO films made in our laboratory, he experimented with a single film flux flow device, originally suggested by Gert Hohenwarter, a Research Associate partially supported by Hypres and Sandia. This device is somewhat analogous to the VFT or the superCIT. This device, which we originally called the Abrikosov vortex flow transistor, AVFT, has been subsequently developed more fully by Martens at Sandia, where it has become known as the superconducting flux flow transistor or SFFT. Our work included high frequency S parameter measurements which showed that this structure is an active device with some high frequency potential[10]. This was followed by a demonstration of the active behavior through the creation of a simple feedback oscillator constructed as an integrated circuit. Stable oscillations up to 12 GHz were observed with one configuration and 40% tunability for a 3 GHz oscillator was obtained[11].

A phase modulator was also made with this device[12]. The modulator displayed wideband, linear modulation over a wide variety of modulation depths. The key to this application appears to be an easily controllable inductance present across the output terminals of the device. Phase modulation for carrier frequencies up to 35.8 GHz were observed. The large nonlinear inductance observed in a similar structure was also investigated by Thompson[13]. A preliminary noise study on the SFFT was made by fellowship student Juan O'Callaghan[14] and the impedance matching problem was addressed by Hohenwarter[15]

The flux flow device has a low input impedance to allow a JJ to drive it efficiently and a higher output impedance (several ohms) with capability for a reasonably large voltage swing to allow better coupling to a FET. A circuit was constructed with an all Nb junction driving the control line of a flux flow device made of TlCaBaCuO. The output voltage of this device was measured to be about 90mV when the junction switched and the response time was <90ps (fixture limited). This could make a useful Josephson line driver for some applications[16].

A double gate structure for the VFT and the SFFT was proposed by Beyer[17]. Examples were fabricated of such SFFT structures and parameter measurements were made in the frequency range of 500MHz to 5 GHz. This device is an electrical dual to the double gate (usually called dual gate) semiconductor field effect transistor. Product mixing was demonstrated at microwave frequencies

The SFFT was not something emphasized in the original proposal for our research. Its success was a surprise. Although Martens attempted a theoretical explanation of this device[18], there are still enough difficulties in making devices repeatably and enough questions concerning its operation, to suggest the need for a more thorough study of the device mechanisms. This is currently being pursued.

E. Related Studies

Although not supported on this grant, three additional graduate students, Miguel Contreras, Ji-Ung Lee and Yifeng Yang, worked on the deposition of BiSrCaCuO thin films by single target rf sputtering. They had succeeded in making good films with a post deposition anneal, however the surfaces were too rough to be able to use for our flux flow devices[19, 20]. Subsequent work using a substrate heater to allow deposition of in-situ films resulted in much improved films, although still containing at least two different phases of this material. Yang has also fabricated various low Tc - high Tc tunnel junctions on this material and on bulk samples of BSCCO to determine the feasibility of making junction devices[21].

Because of the interest in the SFFT and other HTS single film devices, graduate student Bruce Davidson began in 1990, along with fellowship student Ronald Redwing, to design and build an excimer laser ablation thin film deposition system. The equipment money was provided by the University of Wisconsin Graduate School. This equipment is currently making excellent epitaxial YBaCuO films and is being used in conjunction with our current AFOSR grant .

Graduate student Farshid Raissi experimented with a VFT which is fed by a spatially symmetric control line. This structure can be made to operate as an effectively one dimensional version of the flux flow "p-n junction" proposed by Kadin for HTS films. This structure is interesting for new device possibilities. It also appears that it may offer a solution to the resonance problem on short VFTs[22].

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Jin-Shyong Jan, PhD, January 1990
Jon S. Martens, May 1990,
James H, Thompson, PhD, December 1991
Ji Ung Lee, MS, August 1991
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