REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 13, 1995

3. REPORT TYPE AND DATES COVERED
Final Technical: 30 Sept 91 - 31 Jan 95

4. TITLE AND SUBTITLE
Superconductive Electronic Devices Using Flux Quanta

5. FUNDING NUMBERS
~~G-AFOSR-91-0396~~
61102F
2305/GS

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8. PERFORMING ORGANIZATION REPORT NUMBER
DC-98
144-DU64

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
Building 410
Bolling AFB DC 20332-6448

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
afosr 91-0396
AFOSR-TR- 95 - 0456

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This research involved the study of electronic devices using quantized magnetic flux lines in long Josephson junctions and in superconductive films. The work involved fabrication and electrical measurement, coupled with physical modelling, of device configurations . The Josephson structures studied included the junction vortex flow transistor made with both low and high transition temperature superconductors and a niobium device which proved to be an interesting dual to a semiconductor diode. A laser ablation system was built for deposition of the thin films . Films from this system and from other laboratories were used in a coordinated study of the magnetic field sensitivity of thinned links. The results of this study showed too little sensitivity for practical Abrikosov vortex flow transistors to be realized. A parallel study on granular films yielded similar results. It was concluded that Josephson based devices had much more potential. Subsequent study was conducted on grain boundary Josephson junctions and junctions made by oxygen depletion caused by a narrow electron beam. Long Josephson junctions were made and characterized. Vortex flow transistor structures, using long junctions and junction arrays have been designed.

14. SUBJECT TERMS
Superconductive Electronic Devices
Flux Flow Transistors

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTF
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-
Prescribed by ANSI Std Z39-18
298-102

REPORT- Grant No. AFOSR-91-0396

SUPERCONDUCTIVE ELECTRONIC DEVICES USING FLUX QUANTA

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June 13, 1992

Final Technical Report for Period September 30, 1991 through January 31, 1995

Prepared for
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SUMMARY

This research involved the study of electronic device possibilities using quantized flux lines or vortices in long Josephson junction structures and in superconductive films. The work encompassed fabrication and electrical measurement of thin film device configurations coupled with physical device modelling. The long Josephson junction structures studied included the junction vortex flow transistor made with both low and high transition temperature superconductors and a niobium device which proved to be an interesting electrical dual to a semiconductor pn diode. A laser ablation system for deposition of thin films of high transition temperature superconducting materials was built . Films from this system and other films obtained from other researchers were used in a coordinated study of the magnetic field sensitivity of thinned structures of such films. The results of this study showed too little sensitivity for practical Abrikosov vortex flow transistors to be realized. A parallel study on granular films yielded similar results. From this we concluded that Josephson based devices had much more potential. Subsequent device study was conducted on YBCO thin film grain boundary Josephson junctions and junctions made by oxygen depletion using a very narrow electron beam. Long Josephson junctions have been made and characterized. Vortex flow transistor structures, using long junctions and junction arrays have been designed.

RESEARCH OBJECTIVES

The prime purpose of this research was to uncover and evaluate ways to produce electronic device functions using magnetic flux quanta in superconductive thin films. These flux quanta could take the form of so-called Abrikosov current vortices in a uniform film or Josephson vortices in a long Josephson junction. We started with the four objectives, below, and modified them as our knowledge increased.

1. As stated in the original proposal, one objective of this research was to investigate and further develop our ideas for enhancing the frequency response of the hysteretic Josephson junction vortex flow transistor (JVFT). This effort was to involve primarily simulation using models for the various configurations proposed. If one of these ideas appeared promising, we would again pursue high frequency applications of this device such as a distributed amplifier. In either case we intended to also look at low frequency applications, particularly a high gain amplifier.

2. In parallel with this effort on the JVFT, we proposed to fabricate, electrically characterize, and to determine the basic limitations of our, then newly conceived, long Josephson junction vortex-antivortex diode. This device is in some ways a dual to the semiconductor pn diode. If a simple diode functioned as expected, we proposed to proceed to a bipolar transistor structure. Further work would then proceed involving the study of gain, frequency, and noise limitations of this device compared to the JVFT. Because it involves hysteretic Josephson junctions, this effort was to be done using low T_c superconductors.

3. Another aspect of the proposal was to perform low and high frequency testing of the superconducting flux flow transistor (SFFT) to try to determine some fundamental limitations to the gain and frequency response for this device and to develop a suitable model for its behavior. Although it had been assumed that Abrikosov vortices were involved, another possibility was a model consisting of a matrix of Josephson junctions in granular material. For this work, we proposed to make devices for testing and comparison by using high T_c superconducting films from other laboratories as well as our own.

4. In an effort to incorporate higher transition temperature materials into the study of hysteretic Josephson junction devices, we proposed to make BKBO (barium-potassium-bismuth oxide) thin films. We expected to study junction behavior and to attempt to control

granular behavior. The granular study was to include NbN which we already were depositing for Josephson junctions.

RESEARCH STATUS AND 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. The first four numbered sections which follow correspond to each of the four research objectives described above.

1. Hysteretic Josephson Vortex Flow Transistor, (JVFT)

Long Josephson junctions and basic JVFT structures were fabricated using various low T_c thin film techniques including Nb-NbOx-Pb, Nb-AlOx-Nb, NbN-NbOx-Pb and NbN-insulator-NbN combinations. The NbN project had been started under a previous grant and was completed by graduate student David Dawson-Elli during the first year of this grant[1]. The low frequency characteristics were measured and compared various students. The results of these studies and simulations led to a conclusion that the hysteretic device has two major limitations for use as a high frequency amplifier. The first is the low impedance levels, particularly at the input. The second is the existence of unwanted resonances which cause step behavior in the volt-ampere characteristics[2]. The proposed cure for the low impedance levels was a broadband distributed amplifier design. However, this configuration necessitates a number of indirectly coupled devices and the simulations showed an unacceptable capacitive coupling produced between input and output lumped element transmission lines used in the classic distributed amplifier. The resonances can theoretically be eliminated by impedance matching[3] but the complexity of the resulting circuits discouraged further investigation along this line. Work on these structures during the final year of the Grant, involved primarily a computer optimization, by graduate student Mohan Ketkar, of the junction dimensions necessary to allow large gain and small feedback capacitance[4]. As discussed below, more emphasis in the latter part of the grant went toward understanding and fabricating nonhysteretic versions of the VFT using high T_c films.

2. Study of the Vortex-Antivortex Diode Structure

Work was completed on this structure in January 1995 by graduate student Farshid Raissi[5]. Both a simulation[6] and an experimental study[7] were conducted. It was found that this device is indeed a close dual to the semiconductor pn junction diode. The importance of that fact to producing a useful device lies in the possibility of creating a dual to the bipolar transistor. After a number of attempts with Nb-Pb technology, a prototype transistor was realized. A comparison with the JVFT led us to conclude that the latter device is superior because it is a simpler device to build and can have a large current and voltage gain. The bipolar device has a unity voltage gain in its most obvious mode of operation. It is, however, less subject to unwanted resonances than the JVFT. Other modes of operation analogous to, for example, the common emitter configuration of a BJT, have not been attempted.

3. The Superconducting Flux Flow Transistor

A considerable experimental effort led by graduate student Bruce Davidson, and involving most of our graduate students, was devoted to understanding the successes and lack of success in various laboratories with the superconducting flux flow transistor (SFFT). Our results, which were discussed in the second year technical report, were written up and published in 1994[8]. These results reinforced our original assumption (supported by our simulations) that the mechanism for amplification in our early devices depended on the existence of multiple weak links or grain boundary Josephson junctions. An additional effort to understand the characteristics of various weak links was made by students Juan O'Callaghan and Tuong Nguyen through a low frequency noise study[9].

4. High T_c Materials and Configurations for Flux Flow Devices

We never attempted to deposit BKBO. However, considerable initial effort was made on sputter deposition of BSCCO by graduate student YiFeng Yang[10,11,12]. This began as a materials study on a separate grant, but measurements of c-axis conduction on films and subsequently on small mesas etched into bulk single crystals caused us to look more closely at device possibilities. The c-axis conduction behaves as a stack of hysteretic Josephson junctions. To date, graduate student Ji Ung Lee has made long junction stacks[13],[14] and observed high velocity flow of Josephson vortices[15], in agreement with a model by Clem.

Most of our recent concentration has been on YBCO, with which we have had considerable success using a laser ablation deposition system built during the course of this grant. The system was built by by graduate students Bruce Davidson, supported by

AASERT funding associated with this grant, and Ronald Redwing, supported by NSF on a Materials Research Grant.

Three types of device structures were attempted. The first was an effort to create an SFFT structure using granular films by depositing YBCO via a grapho-epitaxial technique on etched substrates. This work, was completed by MS student Nancy Hromdka[16] during 1994. Magnetic field sensitivity of these films was still not large enough to enable building a useful SFFT.

Finally recognizing that the only sure way to make structures with useable gain was to use Josephson junctions, we began an effort with step-edge grain boundary junctions and then changed to a more repeatable process, deposition of YBCO on bicrystal substrates. In parallel with that effort, we have also developed a technique for making junctions by reducing the oxygen content in a very narrow line drawn across a film with an electron beam[17]. New designs for VFT structures have now been made and masks prepared. We have concentrated on nonhysteretic current injection transistor configurations using single or multiple junctions. Some success has been recently made in Europe on multiple junction structures. The electron beam technique allows us more freedom in the physical layout and we expect to be able to produce higher gain structures.

During the course of this grant, J. Nordman has written an extensive review paper on vortex flow amplifying devices[18]. From our work and the work of others, it has become clear at this time that these structures can produce useful amplification using existing high T_c Josephson junctions. Little optimization of gain has been attempted and frequency and noise limitations have yet to be determined.

PUBLICATIONS AND THESES

1. D. F. Dawson-Elli, "On the Processing of NbN-Insulator-NbN Trilayers for Josephson Junction Applications," PhD Thesis, University of Wisconsin-Madison, December, 1992.

2. J. H. Thompson, J. B. Beyer and J. E. Nordman, "Effects of Finite Junction Length on the Vortex-Flow Transistor," J. Appl. Physics, 75, 3662 (1994).

3. J. H. Thompson, M. A. Ketkar, J. B. Beyer and J. E. Nordman, "Elimination of Output Voltage Quantization in the Vortex Flow Transistor, IEEE Trans. Appl. Superconductivity, 1, 2543 (1993).

4. M. A. Ketkar, J. B. Beyer and J. E. Nordman, "Gain Limitations in Narrow Width Josephson Vortex Flow Transistors," Applied Superconductivity Conference, Boston, October 1994. To be published in IEEE Trans. Appl. Superc.

5. F. Raissi, "Josephson Fluxonic Diodes," PhD Thesis, January, 1995

6. F. Raissi, and J. E. Nordman, "Comparison of Simulation and Experiment for a Josephson Fluxonic Diode," Applied Superconductivity Conference, Boston, October 1994. To be published in IEEE Trans. Appl. Superc.

7. F. Raissi, J. E. Nordman, "Josephson Fluxonic Diode," Appl. Phys. Lett.65, 1838 (1994).

8. B. A. Davidson, R. D. Redwing, R. Nguyen, J. O'Callaghan, F. Raissi, J. U. Lee, J. P. Burke, G. D. G. Hohenwarter, J. E. Nordman, J. G. Beyer, S. H. Liou, J. Eckstein, M. P. Siegal, S. Y. Hou, and J. M Phillips, "Magnetic Field Sensitivity of Variable Thickness Microbridges in TBCCO, BSCCO and YBCO," IEEE Trans. Appl. Superconductivity, 4, 228, (1994).

9. T. Nguyen, J. M. O'Callaghan, B. A. Davidson, R. D. Redwing, G. K. G. Hohenwarter, J. B. Beyer, and J. E. Nordman, "Mechanisms for Conduction via Low-frequency Noise Measurements of High-T_c Thin-film Microbridges, Applied Superconductivity Conference, Boston, October 1994. To be published in IEEE Trans. Appl. Superc.

10. Y. Yang, J. E. Nordman, and J. U. Lee, "Effects of Deposition Conditions on Stoichiometry of Off-Axis Rf Sputtered BiSrCaCuO Thin Films," IEEE Trans. Appl. Superc., 3, 1543 (1993).

11. Y. Yang, "Fabrication of Bi-Sr-Ca-Cu-O Superconducting Thin Films And Interface Studies," PhD Thesis, 1993

12. Y. F. Yang, J. U. Lee, and J. E. Nordman, "Effects of Target Presputtering on Stoichiometry of Sputtered Bi-Sr-Ca-Cu-O Thin Films," J. Vacuum Science and Techn., 10, 3288 (1992).

13. J. U. Lee, G. K. G. Hohenwarter, R. J. Kelley, J. E. Nordman, "Low Magnetic Field Sensitivity of C-Axis Transport in BSCCO (2212) Single Crystals," Applied Superconductivity Conference, Boston, October 1994. To be published in IEEE Trans. Appl. Superc.

14. G. K. G. Hohenwarter, A. W. Laundrie, J. U. Lee, J. B. Beyer and J. E. Nordman, "Rf Coupling to Single Crystal BSCCO under C-axis Bias, Applied Superconductivity Conference, Boston, October 1994. To be published in IEEE Trans. Appl. Superc.

15. J. U. Lee, J. E. Nordman, G. Hohenwarter, "Josephson Vortex Flow in Superconducting Single Crystal $Bi_2Sr_2CaCu_2O_x$," Submitted to Applied Physics Letters

16. N. L. Hromadka, "Graphoepitaxially Engineered Granular $YBa_2Cu_3O_7$ Superconducting Films," MS thesis, August 1994

17. B. A. Davidson, R. D. Redwing, T. Nguyen, and J. E. Nordman, "Discrete Vortex Flow Transistors using Electron-Beam Scribed Josephson Junctions in YBCO," International Conference in Capri, Italy, Oct. 1994, entitled "Nonlinear Superconducting Devices and High Tc Materials". To be published in conference proceedings.

18. J. E. Nordman, "Superconductive Amplifying Devices using Fluxon Dynamics," invited review paper to be published in Superconductor Science and Technology.

ADDITIONAL CONFERENCE PRESENTATIONS

B. A. Davidson, R. D. Redwing, T. Nguyen, N. Hromadka and J. E. Nordman, "Device Characteristics of Electron-Beam Written Junction Arrays in YBCO," Applied Superconductivity Conference, Boston, October 1994.

B. A. Davidson, R. D. Redwing, J. E. Nordman, and G. K. B. Hohenworter, "A Comparative Study of Flux Flow Transistors in TBCCO, YBCO and BSCCO Systems," International Superconductive Electronics Conference, Boulder, CO, August 11-14, 1993; extended abstract review.

PERSONNEL

a) People who have received some grant funding

J. B. Beyer, Professor

J. E. Nordman, Professor

Mohan Ketkar, graduate student Research Assistant

David Dawson Elli, graduate student Research Assistant

Bruce Davidson, graduate student RA

Ronald Redwing, graduate student RA

Ji Ung Lee, graduate student RA

Farshid Raissi, graduate student RA

Nancy Hromadka, graduate student RA

b) Others associated with the grant but funded elsewhere

Gert Hohenwarter, Research Associate

Joseph Burke, Graduate Student

Juan O'Callaghan, Graduate Student Fellow

Tuong Nguyen, Graduate Student Fellow, TA

YiFeng Yang, Graduate Student Research Assistant-NSF

DEGREES

David Dawson-Elli, PhD, December 1992

YiFeng Yang, PhD, June 1993 (no grant support)

Nancy Hromadka, MS, August 1994

Farshid Raissi, PhD, December 1994

OTHER ACTIVITIES

J. Nordman was invited to the 8th biennial Workshop on Superconductive Electronics, Ogunquit, Maine, October 3-7, 1993

J. Nordman was invited to write a review paper on fluxonic devices for Superconductor Science and Technology