

Chapter 4. Superconducting and Quantum-Effect Devices

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4.1 Simulations of Vortices in Arrays of Josephson Junctions

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Enrique Trías, Robert D. Bock, Professor Terry P. Orlando, Joel R. Phillips, Dr. Herre S.J. van der Zant, Professor Jacob K. White

Vortices play a central role in determining the static and dynamic properties of two-dimensional (2D) superconductors. Artificially fabricated networks of superconducting islands weakly coupled by Josephson junctions are model systems to study the behavior of vortices. Studies of vortices in Josephson junction arrays generally neglect the magnetic fields induced by currents flowing in the array, i.e., it is assumed that the penetration depth for flux λ is much larger than the size of the array. With the present SNAP technology, all niobium arrays have been made with λ of the order of the cell size, therefore, effect of induced fields must be considered for an accurate description of these systems.

We use numerical simulation to investigate how a variety of vortex static properties are affected by

finite penetration depth λ , and we calculate for the first time the self-consistent current and magnetic fields from a vortex in a 2D array. We find that in order to calculate the correct current and field distributions, the full 3D behavior of the magnetic fields must be accounted for by including nearly all mutual inductance terms. However, to calculate the energy barrier for cell to cell vortex motion—which was first shown by Lobb, Abraham, and Tinkham (LAT)¹ to be $0.2 E_J$, where E_J is the Josephson coupling energy—it is sufficient to include only self- and nearest-neighbor inductances. The LAT calculation neglected induced magnetic fields. We show that induced fields may increase the energy barrier substantially above $0.2 E_J$. Our calculations also show that (1) the thermodynamic lower critical field of the array is enhanced when the computation self-consistently accounts for induced magnetic fields, and (2) by using only a self-inductance term to model the induced fields, the lower critical field is overestimated.

Measurements and numerical studies of the self-field effects in arrays of Josephson junctions have been performed. For two-dimensional arrays, we find that the mutual inductive couplings among all the cells of the array must be included to correctly model the current and magnetic field distributions; whereas, for one-dimensional arrays of parallel junctions, these static properties can be modeled well by just including the nearest neighbor cou-

¹ C.J. Lobb, D.W. Abraham, and M. Tinkham, "Theoretical Interpretation of Resistive Transition Data from Arrays of Superconducting Weak Lines," *Phys. Rev. B* 27: 150-157 (1983).

plings. The lower critical field and the energy barrier for depinning are found to increase as the self-inductance becomes more important, and we verify these numerical results with measurements on both one- and two-dimensional arrays of niobium junctions. We have also simulated and measured some dynamical properties of arrays. For example, measurements of the Fiske modes and Eck peaks in one-dimensional arrays allow measuring the self and mutual inductances directly. Likewise, current-voltage characteristics of two-dimensional arrays show that the flux-flow resistance increases as the self-field effects become more important, reflecting the decrease of the effective mass of the vortex.

4.2 Superconducting Transmission Lines

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Laurence H. Lee, Professor Jacob K. White, Professor Terry P. Orlando, in collaboration with W.G. Lyons²

A full-wave spectral-domain volume-integral-equation method has been developed to analyze various configurations of superconducting transmission lines: microstrip lines, striplines, coplanar strips, and coplanar waveguides. In the formulation, a spectral-domain Green's function for isotropic, layered media is used to set up an integral equation for the electric field inside the superconducting strips. Galerkin's method with roof-top basis functions is employed to solve for the complex propagation constant and current distribution. The characteristic impedance of the structures is then obtained from transmission line theory. This method rigorously accounts for the anisotropy and the finite thickness of the superconducting films, yielding accurate characterization for the loss and kinetic effect of the superconductors. However, this technique is computationally inefficient.

To implement an efficient method, an equivalent surface impedance is used to transform the superconducting strip with finite thickness to an infinitely thin strip. This equivalent surface impedance

accounts for the loss and kinetic inductance of the superconductors. An empirical formula for the current distribution in a thin superconducting film is determined for the derivation of the equivalent surface impedance. To include effects of anisotropic substrates, a 2D dyadic Green's function for anisotropic, layered media is used to formulate an integral equation for the surface current. Galerkin's method with entire-domain basis functions is used to solve for the complex propagation constant and the surface current. The characteristic impedance is then calculated using the power-current definition. This method has been used to analyze superconducting single and coupled microstrip lines on anisotropic substrates.

A closed-form expression was found for the current distribution in an isolated strip made from a superconducting thin film with thickness less than a few penetration depths. This equation gives a good approximation within certain limits for the resistance and inductance per unit length of superconducting striplines and microstrip lines. Both the ac resistance of an isolated superconducting strip and the resistance per unit length of a superconducting stripline calculated using this closed-form expression agree well with the numerical results generated by the modified Weeks' method. It is now possible to use this expression along with the integral equation method to develop an efficient full-wave method for analyzing superconducting planar transmission lines.

4.3 Discrete Superconducting Vortex Flow Transistors

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Dr. Herre S.J. van der Zant, Professor Terry P. Orlando, in collaboration with Dr. K.A. Delin³

Vortex flow transistors (VFT) are the focus of renewed interest since a discrete flux flow device made of weak links in a high-temperature film demonstrated promising results. Current gains higher than one, transresistances of the order of 10 Ω , a maximum output voltage of about 20 mV, and

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³ Conductus, Sunnyvale, California.

speeds of the order of 50 ps were obtained. Flux-flow devices were proposed more than ten years ago and were fabricated in a long continuous Josephson junction. There are two versions of a VFT in long Josephson junctions; one is a device made of a long overdamped junction (the McCumber parameter $\beta_c < 1$) and the other is made with an underdamped junction ($\beta_c > 1$). The disadvantage of long Josephson junctions is that the output resistance is low (much smaller than 1Ω) and that the output voltage is generally much smaller than 1 mV. Moreover, it is difficult to manipulate the parameters and improve the response time of the device. Discrete vortex flow transistors (DVFT) overcome these difficulties.

We have fabricated discrete overdamped vortex flow transistors (DVFTs) made of short niobium Josephson tunnel junctions connected in parallel. The results of our DVFT were compared with the high- T_c devices and long continuous Josephson junctions. We have also done model calculations on our DVFT which are in good agreement with our experimental results. We calculated the current gain, transresistance, output voltage, and output resistance. Our model is also applicable to other 1D discrete systems and can also be used to model long Josephson junctions. Our analysis shows that when disregarding the lower temperatures and voltage levels in low- T_c materials, DVFTs made of niobium tunnel junctions can perform at the level comparable to the present high- T_c flux flow devices.

4.4 Fiske Modes in One-Dimensional Parallel Josephson-junction Arrays

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David Berman, Dr. Herre S.J. van der Zant, Professor Terry P. Orlando, in collaboration with Dr. K.A. Delin³

We have performed measurements on one-dimensional (1D) arrays of underdamped Josephson junctions connected in parallel by superconducting wires which in a magnetic field show resonances in the current-voltage characteristics. From analytical calculations, we find that the position of the steps is determined by the dispersion relation $\omega(k)$ of a 1D discrete, linear transmission line, where the Josephson junction has been replaced by the capacitor and the resistance of the junction. When nearest-neighbor inductances are accounted for, the model agrees well with the

measured positions of the steps. Numerical calculations of the full dynamics with inclusion of inductances between all cells support our model. As an example of a system with more complicated dispersion, we have measured 1D arrays with two different junctions per primitive cell. The measured dispersion relation shows an acoustic and an optical branch in agreement with numerical simulations of the full dynamics.

4.5 Novel Mesoscopic Superconducting Devices

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Professor Dimitri A. Antoniadis, James J. Huginin, Professor Terry P. Orlando, Professor Henry I. Smith

Superconductor/semiconductor contacts are fabricated between V_3Si and Si by a solid-phase reaction between SiO_2 and V. Auger spectroscopy is used to confirm the presence of the V_3Si phase, the sheet resistance versus temperature of the device is measured to determine a superconducting transition temperature of 14 K.

The electrical properties of the V_3Si/Si interface are examined for cases where the V_3Si is in both normal and superconducting states. The first two measurements are performed at room temperature and are used to investigate the two forms of transport for normal electrons, either through or over a Schottky barrier. The second set of measurements are performed between 17 K and 0.3 K and are used to examine the properties of this interface as the superconducting energy gap increases in the V_3Si . Each of these three experiments shows a Schottky barrier height of about 0.16 eV for the V_3Si/Si interface. In addition, the low temperature measurements confirm that this interface is that of a superconductor/semiconductor.

There are two anomalies in this experiment. First, the current flow through the contacts is approximately 10^6 times smaller than that expected for contacts of the given area, indicating some flaw in the fabrication process. Second, low temperature measurements reveal unexpected structure near 0.5 meV. It is speculated that this is related to the presence of a superconducting phase of another vanadium compound.

4.6 Single Charging Effects and Tunneling in Quantum Dot Nanostructures

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Professor Dimitri A. Antoniadis, Martin Burkhardt, David J. Carter, Arvind Kumar, Professor Terry P. Orlando, Professor Henry I. Smith

Quantum-effect devices, whose feature size is comparable to the Fermi wave-length (about 50 nm in a typical inversion layer), have great potential in novel electronics applications because of their nonlinear characteristics. Such tunneling devices were fabricated using x-ray lithography and measured at cryogenic temperatures. The devices were fabricated on modulation doped AlGaAs/GaAs substrates. After mesa etch and deposition of ohmic contacts, x-ray lithography was used to put down the gate patterns. The finished device had minimum line widths below 70 nm.

This work focuses on the study of GaAs quantum dot devices in which an electron gas is electrostatically confined to a small conducting island. The device dimensions are sufficiently small that striking effects due to the capacitive charging of the island by a *single* electron can be observed in the transistor characteristics, leading to a *periodic* dependence of the current on gate voltage. In particular, we study a quantum dot structure in which a novel gate geometry allows the island to be contacted by three electron reservoirs. When the dot charge is well-confined, periodic conductance oscillations due to Coulomb charging are observed in-phase with each other at two of the leads in response to small excitation voltage at the third. As the tunnel barriers are made softer by changing the gate voltage, a strikingly different phenomenon is observed: conductance peaks at the two output leads evolve from perfect *correlation* to perfect *anti-correlation* with each other. Two simple models of transport in the weakly blockaded regime are presented as possible explanations.

4.7 One-dimensional Parallel Josephson-junction Arrays as a Tool for Diagnostics

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Project Staff

A.W. Kleinsasser,⁴ Professor Terry P. Orlando, Roger A.M. Receveur, Dr. Herre S.J. van der Zant

We propose and demonstrate the use of underdamped, one-dimensional parallel arrays of Josephson junctions as a tool for circuit diagnostics. By measuring the Fiske modes and the critical current in a magnetic field, we determined the self- and nearest-neighbor inductances as well as the capacitances of single junctions. We have used this technique to find the capacitance of Nb-Al₂O_x-Nb junctions for critical current densities of 0.3 - 20 kA/cm². We find that the specific capacitance increases by about a factor of 2 over this range. This increase has important consequences for the design of single-flux-quantum circuits and SQUIDs. Measurement of the junction capacitance for critical current densities of 100 kA/cm² is possible, but requires submicrometer junctions with dimensions of the order of 0.3 μm.

4.8 Nonlinear Dynamics of Discrete Josephson Rings

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Professor Terry P. Orlando, Steven H. Strogatz, Dr. Herre S.J. van der Zant, Shinya Watanabe

We have studied the dynamics of circular one-dimensional arrays of underdamped Josephson junctions connected in parallel. In these Josephson rings, a single vortex can be trapped and studied experimentally without the complications caused by reflections off boundaries. We find that a propagating vortex can become phase-locked to linear waves excited in its wake. In the *IV* curve, resonant steps are observed indicative of this phase-

⁴ IBM Corporation, Thomas J. Watson Research Center, Yorktown Heights, New York.

locking. Their position is well predicted by theory and, numerical simulations indicate that, at least in principle, an infinite number of these steps is possible. Resonant steps also occur in the IV curves for higher voltages in the return path of the subgap region. These resonant steps have a completely different origin. They occur at voltages where the periodic whirling solution destabilizes itself by parametrically exciting the linear modes of the system. Only $N/2$ of these steps are possible, with N the number of junctions in the ring. Despite the presence of linear modes, our numerical studies show that a single propagating vortex can be viewed for a certain range of parameters as a particle with a long mean free path. This almost free vortex propagation makes discrete Josephson rings ideal systems for further quantum vortex experiments.

4.9 Discrete Underdamped Vortex Flow Devices

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Project Staff

Amy E. Duwel, Professor Terry P. Orlando, Dr. Herre S.J. van der Zant

Parallel arrays of Josephson junctions behave, in many ways, like long, continuous junctions. Both structures may be used as superconducting circuit elements, such as transistors, oscillators, phase shifters, and amplifiers. These systems also serve as valuable models for high-temperature superconducting devices.

Vortex flow devices consisting of discrete arrays of underdamped Josephson junctions have been fabricated and measured. These devices and their long, continuous junction counterparts are based on the ability to magnetically control the Eck voltage in an underdamped system. We find that both transistor and oscillator parameters are improved by placing the arrays above a superconducting ground plane and by connecting two arrays in series. We developed models for the device behavior which numerically account for the measured parameters. Our models also suggest that junctions with smaller capacitances will further improve the device parameters.

4.10 Publications

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