A Microscopic Examination of the Josephson Junction

J. K. Freericks, P. Miller, and M. Jarrell

Department of Physics, Georgetown University,
Washington, DC 20057
freericks@physics.georgetown.edu
(202) 687-6159 (voice) (202) 687-2087 (fax)
Introduction

- The Josephson-Junction Computer
- Maximize $I_c R_n$
- Resistively Shunted Junction Model

\[ \tau = \frac{\hbar}{e I_c R_n} \]
Navy Interest

• High precision, high speed, analog-digital converters for advanced radar design (up to 20 bits of resolution and speeds in excess of 200GHZ)

• Employ High-Temperature Superconductor Technology
Background

- Insulator $\rightarrow$ high $R_n$ low $I_c$
- Metal $\rightarrow$ low $R_n$ high $I_c$
- Are properties optimized near the metal-insulator transition?
- What type of material produces the best JJ weak-link region?
Metal-Insulator Transitions

- Anderson (disorder, mobility edge)
- Mott-Hubbard (correlations)
- Periodic Anderson Model (f-electrons, Kondo effect)
- Holstein (bipolaron self-trapping)
- Falicov-Kimball (thermodynamics of localized and interacting electrons)
Bogoliubov-DeGennes Equations

• Static Hartree-Fock approximation (self consistent solution)
• Superconducting gap varies with position, and acts like a mean-field potential in the reduced Hamiltonian
• Numerical solution is problematic for large systems (mainly due to the self-consistency)
Blonder-Tinkham-Klawijk Model

• Simplification of B-DG, not self-consistent

Square well plus an interface potential

IV characteristics

J. K. Freericks, Georgetown University, Office of Naval Research, Program Review, 1999
New Approach

- Self-consistent solution
- Includes dynamical effects (retardation, nonconstant DOS, vertex corrections, local fluctuations, etc.)
- Exact solution through the MI transition (including all local correlation effects)
- Theoretical optimization of $I_c R_n$
Methodology

- Inhomogeneous planar system
- Local self energy on each plane
- Reduces to a quasi-1D “tight-binding” problem at each planar momentum plus a dynamical MFT
Details of Algorithm

Algorithm is iterated until a self-consistent solution is achieved

- Self-energy on each plane
- Quasi 1D model (RPE)
- Planar Green’s functions
- Sum over planar momenta
- Local Green’s function
- Dyson’s equation
- Effective Medium
- DMFT
Comparison of Methods

\[ F(\tau = 0) = \langle c^+ c^+ \rangle \]

- Computational time reduced by a factor of 1000 versus a direct solution of the B-DG equations
- Compared to the DMFT at the HF level

J. K. Freericks, Georgetown University, Office of Naval Research, Program Review, 1999
Summary of Algorithm

- Fast
- Includes dynamical effects
- More realistic model of the JJ weak-link region
- “Black Box” method to study different kinds of superconductors and interface materials
Superconductors

- Migdal-Eliashberg materials (Nb, Pb, Al, etc.)
- Vertex-corrections or nonconstant density of states (BKBO, Nb-doped Strontium titanate, doped fullerenes)
- D-wave superconductors (YBCO, BSCCO, etc.)
- Heavy-Fermions
Example Weak-Link (FK model)

- Conduction electrons that hop between lattice sites
- Localized electrons which are limited to one per site
- Coulomb interaction only between localized and itinerant electrons
- Metal-Insulator transition driven by thermodynamics

J. K. Freericks, Georgetown University, Office of Naval Research, Program Review, 1999
FK model phase diagram

Phase Diagram FK Model

conduction electron density

Insulator

Metal

$t^*/T$

J. K. Freericks, Georgetown University, Office of Naval Research, Program Review, 1999
Example Weak-Link (Holstein Model)

- Bipolaronic Insulator
- Conduction electrons with a hopping $t$
- Einstein phonons (harmonic or anharmonic)
- Linear coupling between the electron number and the phonon coordinate

- Bipolaronic Insulator

J. K. Freericks, Georgetown University, Office of Naval Research, Program Review, 1999
DOS, static Holstein model

- Asymmetry caused by the anharmonic interactions
- Note gap formation as Tc is approached
ONR collaborations and open questions

• (Price and Rogers) Nb superconductor and Nb-doped STO weak-link; YBCO superconductor and Nb-doped STO weak-link

• (Greene) Nb superconductor and InAs weak-link

• Interface roughness effects (neglected here, but can be included by employing phenomenology and results from these microscopic models)

• Experimental results on JJs made from other materials
Conclusions

• Theoretical optimization of the JJ
• Model includes dynamical effects and real material properties
• “Black box” nature allows examination of a number of different SC’s and weak-links, including HTSC’s
• Does not include any interface roughness effects