Superconductor-Correlated metal-Superconductor Josephson junctions for high-speed digital electronics

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Digital Electronics and RSFQ logic

- **Rapid single-flux quantum logic** is used for high-speed applications. A loop of superconducting material has one JJ interrupting it. The absence or presence of a flux quantum in the loop is the binary 0 and 1 of the device.

- The flux is changed by generating a **voltage pulse** through the junction, whose time integral is equal to a flux quantum. Since the voltage scale is set by the product $I_cR_n$, which is on the order of a few mV in low-Tc superconductors, **operating speeds of up to 770 GHz** have been already demonstrated.

- New superconducting materials like $\text{MgB}_2$ and novel barriers like $\text{TaN}_x$ show a promise for even higher characteristic voltages, and hence faster operating speeds of circuits.
Navy Interest

- 100 GHz low phase noise clocks for running ultrafast electronic circuitry.
- Superconducting digital electronics may provide the solution.
- The theoretical calculation and modeling is a scalable massively parallel solution to a scientific problem. The computational engine can have application to other nanoscale electronics design and optimization of interest to the community.

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Optimization of the speed of a JJ

- Three elements are needed for high speed digital electronics based on JJs: (i) a large figure-of-merit \( I_cR_n \); (ii) good thermal stability of the characteristic voltage within the operating temperature range; and (iii) nonhysteretic current-voltage characteristics.

- Can the next generation of JJ technology be built out of a new class of SCmS junctions where the correlated metal barrier has its thickness and metallicity tuned to lie close to the metal-insulator transition?
Many-Body Formalism

- **Inhomogeneous system**, with planes stacked along the z-direction.

- $$H = - \sum t_{ij} c^*_{i\sigma} c_{j\sigma} + \sum U_i n_{i\uparrow} n_{i\downarrow} + \sum U_{FK} (n_{i\uparrow} + n_{i\downarrow}) w_i$$

- Local dynamical correlations are explicitly included for each plane via the **dynamical mean field theory**. The self-consistency relation is now modified to include effects that couple the effective medium between the planes.

- The superconductor is described by the H-F approximation, which is identical to a **self-consistent solution** of the Bogoliubov-deGennes equations for a short-coherence length, s-wave superconductor. The correlated metal is described by an exact form of the **coherent-potential approximation** which displays a metal-insulator transition.

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The Falicov-Kimball model has a metal-insulator transition that occurs as the correlation energy $U$ is increased. The interacting DOS shows that a pseudogap phase first develops followed by the opening of a true gap above $U=4.9$ (in the bulk). Note: the FK model is not a Fermi liquid in its metallic state since the lifetime of excitations is always finite.
Bulk superconducting properties

- $T_c = 0.112t$, $\Delta = 0.198t$, $2\Delta/k_B T_c = 3.56$ --- behaves like a BCS superconductor
- Bulk coherence length $\xi_S = 3.7a = v_F^S / \pi \Delta$ --- short coherence length superconductor

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Thouless energy

• The Thouless energy measures the quantum energy associated with the time that an electron spends inside the barrier region of width $L$.

$$E_{Th} = \frac{\hbar}{t_{Dwell}}$$

• A unifying form for the Thouless energy can be determined from the resistance of the barrier region and the electronic density of states:

$$E_{Th} = \frac{\hbar}{2e^2 \int d\omega N(\omega) \frac{df(\omega)}{d\mu} R_N a^2 L}$$

• This form produces both the ballistic $E_{Th} = \frac{\hbar \nu_F^N}{\pi L}$ and the diffusive $E_{Th} = \frac{\hbar D}{L^2}$ forms of the Thouless energy.

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Length scales

- The **Fermi wavelength** is determined by the inverse wavevector at the Fermi surface (here $\lambda_F \sim 2a$).

- The bulk **superconductor coherence length** is $\xi_S = \xi v_F^S/\pi \Delta$ (here $\sim 3.7a$).

- The **Josephson junction coherence length** $\xi_0$ is found by determining the width $L$ when the Thouless energy is equal to the superconducting gap ($E_{th} = \Delta$). This produces the well-known results of $\xi v_F^N/\pi \Delta$ in the ballistic case and $\sqrt{\xi D/\Delta}$ in the diffusive case (here $\xi_0 < 4a$).

- The **barrier coherence length** $\xi_B$ is found by determining the width $L$ when the Thouless energy is equal to the thermal energy ($E_{TH} = \pi k_B T$). This produces the well-known results of $\xi v_F^N/\pi k_B T$ in the ballistic case and $\sqrt{\xi D/2\pi k_B T}$ in the diffusive case (here $\xi_B < 40 a$).

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Critical current yields barrier coherence length (low T)

- Exponential fit of the critical current for: (i) ballistic metal; (ii) weakly correlated metal; (iii) strongly correlated metal (pseudogap); and (iv) correlated insulator.

\[ I_c = A L^x \exp \left[ -L / \xi_B \right] \]

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The bulk coherence length $\xi_S$ determines the decay of $F$ in the SC, the JJ coherence length $\xi_0$ determines the initial decay from the SN boundary, and the barrier coherence length $\xi_B$ determines how $F$ decays at the center of the barrier.

- At low $T$ oscillations develop in $F$ when the barrier becomes correlated. One can also see Fermi wavelength oscillations. The barrier oscillations rapidly disappear as $T$ increases. The oscillations in the superconductor are only slightly reduced as $T_c$ is approached.

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“Ballistic” SNS and SINIS junctions

- At low T, the JJ coherence length is much smaller than the barrier coherence length, hence one can enter a regime where $\xi_0 \ll L \ll \xi_B$. Here $I_{cRn}$ will be independent of $L$ for a range of $L$, but because $F$ has been reduced on the length scale of $\xi_0$, we expect $I_{cRn}$ to be diminished.

- This phenomenon has been seen by Klapwijk’s group on NbInAsNb JJs!

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Quasiclassical theory predicts a **universal form for dirty metals**, but we see different behavior for the correlated insulator which predicts a greater sensitivity to "intrinsic pinholes".

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Optimization of IcRn

- We reproduce the AB result of IcRn independent of the properties of the insulator for thin junctions, but our value for IcRn is reduced by about 15% due to the inverse proximity effect.

- IcRn grows, seemingly without bound for a bilayer, but we expect hysteresis to enter as the barrier becomes more insulating.

- IcRn is maximized just on the insulating side of the MIT for moderately thick junctions!

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Thermal properties

- Thin insulating junctions follow the AB prediction exactly (solid line)!
- SCmS junctions suffer a faster initial drop for 0<T<0.3Tc, but then the slope becomes similar to that of the AB form for 0.3Tc<T<0.7Tc. Since the curve is only reduced by about 15-20% in this range, the 50% increase of IcRn at low T wins and properties of this junction are superior to self-shunted SIS!
- SNS junctions have poor thermal stability and will not function well in circuits.

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Benefits of SCmS junctions

- When properly optimized for thickness and proximity to the MIT, SCmS junctions have significantly enhanced IcRn products.
- The thermal stability of SCmS junctions over the reasonable operating range of 0.3Tc-0.7Tc is as good as the best case of an SIS junction.
- Overall SCmS junctions can have the best properties of any proposed junction type.

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Potential problems of SCmS junctions

• SCmS junctions may need fine-tuning to reach the “optimization zone”.

• Intrinsisic pinholes may appear if the JJ coupling is highly sensitive to the thickness of the junction (producing dead zones or hot zones that can dominate the JJ effect).

• Fabrication uniformity may be difficult to achieve.
Outstanding Technical Issues

• Generalize the formalism to calculate nonequilibrium effects needed to determine IV characteristics, to calculate subgap structure, and to determine when hysteresis enters.

• Develop a many-body-theory model for the MIT in bulk TaN.

• Incorporate more realistic real materials modeling for NbTiN-TaN-NbTiN SCmS junctions.

• Develop a multiband and multigap version of the computational engine to model MgB$_2$ including realistic sheets of the Fermi surface and of the intra and interband electron-phonon coupling.

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Conclusions

- Examined properties of a Josephson junction tuned through a metal-insulator transition.
- Saw that optimization of the characteristic voltage requires a careful understanding of the correlations, thickness, and operating temperature of the device.
- Found an optimization on the insulating side of the metal-insulator transition for moderately thick barriers in the range $0.3T_c<T<0.7T_c$.
- Discovered that temperature effects are similar to the best case of an SIS junction in the expected operating range for a circuit.
- Conjecture that an “intrinsic pinhole effect” may make fabrication uniformity difficult for SCmS junctions.

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