

Quantum Metastable States in Superconducting Graphene Josephson Junction Devices

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Abstract— We report on the proposed existence and measurement of quantum metastable states in a current-biased, graphene-based Josephson junction. This device consists of two superconducting leads contacted by a single- or few-layer graphene flake. This type of graphene-based junction has been shown to demonstrate the superconducting proximity effect and the Josephson effect in the form of supercurrents. This motivates the investigation of possible metastable quantum states that are trapped in the wells of the associated washboard potential of this device. The small capacitance of the device leads to very large plasma frequencies. A shunting capacitor can be added to lower the plasma frequencies to less than 10 Ghz.

I. INTRODUCTION

Since their discovery in 2004 [1], the electronic properties of Graphene have inspired a flourishing field of research. Graphene is a two-dimensional, hexagonal array of carbon atoms that effectively contains relativistic Dirac electrons. Its characteristic linear dispersion relation near the Fermi energy [2] has led to novel and interesting physics and applications.

Recent studies [3]-[6] have demonstrated the robust and reproducible phenomenon of Josephson supercurrents in devices consisting of two superconducting leads contacted by flakes of graphene that are 1-4 layers thick. Clear evidence of multiple Andreev reflections [5]-[6] illustrates that such graphene junctions behave as SNS junctions. A dc-SQUID has been constructed using graphene [7] and shown to demonstrate several advantages, including how graphene is straightforward to fabricate, electrically contact with high-transparency electrodes, and functionalize using its conduction layer.

Among the most appealing aspects of using graphene for Josephson junction devices is the ability to tune the critical current simply by adjusting a gate voltage [3],[8]. Also, in conventional junctions, dielectric loss from the insulating oxide in the tunnel barrier has been shown to be a dominant source of decoherence in superconducting phase qubits [9]. By reducing the area of the tunnel junction, dramatic improvements in coherence times have been seen [10]. Graphene's pristine crystal structure, its phase coherence over a scale of $\sim 1 \mu\text{m}$ [5] and the absence of a native oxide needed to create a weak link suggest that graphene devices could quite possibly be used to construct superconducting qubits. These physical properties of graphene junctions motivate the investigation of potential metastable quantum states in these graphene devices.

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II. DEVICE FABRICATION AND CHARACTERIZATION

Graphene-based Josephson junctions are made by depositing mechanically exfoliated graphene flakes onto a silicon dioxide substrate [1]. Candidate flakes consisting of 1-4 atomic layers are identified using an optical microscope; even single-layer flakes are visible due to thin-film interference [11]. The precise thickness is determined using Raman spectroscopy [12]. The Raman spectrum in Fig. 2 is taken from the flake shown in Fig. 1.



Fig. 1. An optical image of a candidate graphene flake. The circle shows the location of the laser spot used to obtain the Raman spectrum in Fig. 2.

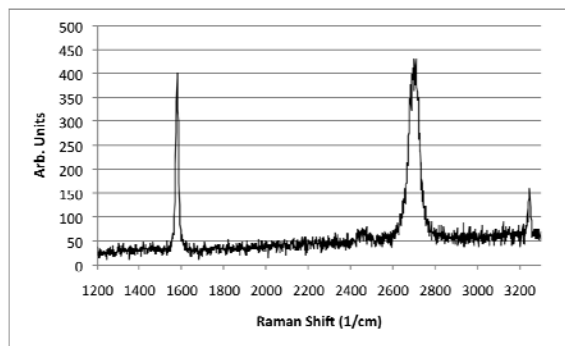


Fig. 2. Raman spectrum of the flake shown in Figure 1. The prominent peak at $\sim 1580 \text{ cm}^{-1}$ is called the G peak and the one at $\sim 2700 \text{ cm}^{-1}$ is called the 2D peak (or historically G') [12]. The ratio of the peak heights, and the positions of the peaks are a signature of the thickness of the graphene flake.

A pair of parallel Ti/Al leads is deposited onto the graphene flake. Titanium provides a transparent adhesion layer and at low temperatures, Aluminum becomes superconducting. Due to the superconducting proximity effect [3]-[4], the areas of graphene around the leads become superconducting as well. The lead separation L is typically between 100 and 500 nm.

III. THEORY

The quantum metastable states we are investigating are analogous to those existing within the wells of the tilted

washboard potential of a current-biased Josephson junction [13]-[14]. This potential has the form

$$U(\gamma) = -(\Phi_0/2\pi)(I_0 \cos \gamma + I_b \gamma) \quad (1)$$

where γ is the gauge-invariant phase difference across the junction, Φ_0 is the flux quantum, I_0 is the superconducting critical current, and I_b is the bias current. For a junction with capacitance C , this potential can be thought as having an analogous classical “phase particle” of mass $C(\Phi_0/2\pi)^2$ with plasma frequency [13]

$$\omega_p = \sqrt{2\pi I_0 / \Phi_0 C} \quad (2)$$

At biasing currents $I_b \sim I_0$, the energy level spacing of the metastable states are $\hbar\omega_{01} \approx \hbar\omega_p$ [15].

The critical current of a graphene junction depends strongly on the aspect ratio of the normal region in between the superconducting leads. Near the Dirac point [2] of the graphene junction and for a large aspect ratio W/L , where W is the length of the leads and L is the normal region width, the theoretical superconducting critical current I_0 is [16]

$$I_0 = 1.33 (e\Delta_0/\hbar)(W/\pi L) \quad (3)$$

where Δ_0 is the superconducting energy gap. The superconducting gap for bulk Al is $\Delta_0 = 180 \mu\text{eV}$; however, experimentally determined values [15] for Δ_0 ranged from 90 to 120 μeV . Making the approximation of $\Delta_0 \approx 100 \mu\text{eV}$, and using a typical aspect ratio of $W/L = 10$ [3],[4],[8], we estimate the critical current to be $I_0 \approx 20 \text{ nA}$.

Due to the geometry of the graphene junction, the inherent capacitance is quite small. From Equation (2), the characteristic frequencies are on the order of several hundreds of Ghz. Typical desired frequencies are in the range $\omega_{01}/2\pi \approx 1 - 20 \text{ Ghz}$. To bring down frequencies to this range, we propose to shunt the device with a capacitance between 10 fF and 1 pF.

IV. EXPERIMENTAL APPARATUS

The quantum states of graphene junctions can be detected using the same microwave spectroscopy technique used to detect quantum states in conventional Josephson junctions [13],[15]. As the bias current through the junction is ramped, the energy level spacings between adjacent states is swept through the frequency of microwave excitation. At resonance, there is an enhancement in the escape rate. Quantum state detection experiments are performed in a helium dilution refrigerator with a base temperature of 9 mK. To reduce thermal noise on the bias and signal lines, we use a combination of Thermocoax cables and home-made low pass LC filters with a rolloff frequency of 10 Mhz.

A gate voltage, V_g , is coupled to the doped Si/SiO₂ substrate. This allows the density of charge carriers to be tuned, using holes or electrons. Differential conductance measurements as we sweep the gate voltage allows us to observe the number of layers in the graphene flake as measured by appearance of the anomalous integer quantum Hall effect [2]-[4].

V. CONCLUSION

We have proposed the existence of metastable quantum states in graphene-based Josephson junctions and a measurement scheme to detect these states in the microwave regime. Detection of such quantum states opens up the potential for a variety of graphene-based quantum devices including superconducting qubits with critical currents that are tunable with a gate voltage.

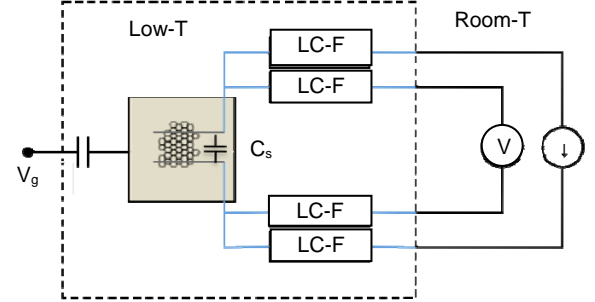


Fig. 3. Schematic of the proposed measurement apparatus with gate voltage V_g , shunting capacitor C_s , LC filters, and Thermocoax lines that filter high-frequency noise. The current source and voltmeter are for differential conductance measurements via four-point probe, and for current biasing and spectroscopy measurements.

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