Magnetic field compatible circuit quantum electrodynamics with graphene Josephson junctions

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Circuit quantum electrodynamics has proven to be a powerful tool to probe mesoscopic effects in hybrid systems and is used in several quantum computing (QC) proposals that require a transmon qubit able to operate in strong magnetic fields. To address this we integrate monolayer graphene Josephson junctions into microwave frequency superconducting circuits to create graphene based transmons. Using dispersive microwave spectroscopy we resolve graphene’s characteristic band dispersion and observe coherent electronic interference effects confirming the ballistic nature of our graphene Josephson junctions. We show that the monatomic thickness of graphene renders the device insensitive to an applied magnetic field, allowing us to perform energy level spectroscopy of the circuit in a parallel magnetic field of 1 T, an order of magnitude higher than previous studies. These results establish graphene based superconducting circuits as a promising platform for QC and the study of mesoscopic quantum effects that appear in strong magnetic fields.
superconducting transmon qubit resilient to strong magnetic fields is an important component for proposed topological and hybrid quantum computing (QC) schemes. A transmon qubit consists of a Josephson junction (JJ) shunted by a large capacitance, coupled to a high quality factor superconducting resonator. In conventional transmon devices, the resonator is fabricated from Al and the JJ is fabricated from an Al/AlOx/Al tunnel junction, both of which cease operation above the critical magnetic field of bulk Al, ~10 mT. Even when considering alternative type II superconductors such as NbTiN or MoRe that can sustain superconductivity beyond \( B = 8 \, \text{T} \), when subjected to a strong magnetic field the superconductor will experience detrimental effects such as reduction of the superconducting gap, increased quasiparticle generation and the formation of Abrikosov vortices that cause resistive losses in a microwave field. In addition to disrupting the superconductivity, magnetic flux penetrating the JJ produces electron interference effects that reduce the Josephson energy \( E_J \) and strongly suppress the transmon energy spectrum. If the transmon is to be used for fast quantum gates, fast charge-parity detection and long range quantum state transfer in QC schemes, we are compelled to consider alternatives to conventional Al based JJs. Proximitised semiconducting nanowires, acting as gate-tunable superconductor-normal-superconductor JJs have been used successfully in a variety of microwave frequency superconducting circuits, allowing for studies of Andreev bound states and long range quantum state transfer in QC schemes. In this work, we present results from two typical graphene transmon devices. It consists of four /4,15,16 transmons that exhibit ballistic nature of our graphene JJs. We perform microwave spectroscopy we resolve the characteristic band dispersion of graphene (Fig. 2). A magnetic field \( B \) can be applied parallel to the plane of the graphene with the graphene junction, with the gate, junction and contacts visible. At negative \( V_G \) = \( V_{\text{CNP}} \), the chemical potential \( \mu \) is below the CNP and the graphene is in the p-regime where holes are the dominant charge carrier. Deep into the p-regime, the high carrier density \( n_c \) gives a large \( E_h \) placing \( f_J \) above the resonator and giving \( \gamma \) a small negative value (Fig. 2c). As \( V_G \) approaches the CNP, the Dirac dispersion minimises the density of states reducing \( E_h \) and \( f_J \) to a minimum. Since \( \gamma = 2g^2/\Delta \), as \( \Delta \) approaches zero, \( \gamma \) diverges. Once on resonance, the resonator acquires some characteristic of the qubit, significantly broadening the lineshape. Simultaneously, the critical photon number \( n_{\text{crit}} = \Delta^2/4g^2 \) collapses, moving the measurement into the ‘transitional’ regime between high and low photon number as in Fig. 2a, causing the anomalous lineshapes visible in Fig. 2c near CNP. As \( V_G \) is increased past the CNP, \( n_{\text{crit}} \) and the lineshapes recover, with electrons becoming the dominant charge carrier and \( E_h \) increasing to a maximum as expected from removal of the n-p junction formed by the contacts. The p-regime also experiences periodic fluctuations in \( E_h \) as a function of \( V_G \) due to coherent electron interference effects in a Fabry–Perot cavity formed by n-p interfaces at the MoRe contacts. Extracting a line

Results

Device structure. Figure 1a shows an optical microscope image of a typical graphene transmon device. It consists of four \( \lambda/4 \) coplanar waveguide (CPW) resonators multiplexed to a common feedline. Each resonator is capacitively coupled to a graphene transmon, with the graphene JJ being shunted by capacitor plates that provide a charging energy \( E_C \approx 360 \, \text{MHz} \). The resonators and capacitor plates are fabricated from 20 nm NbTiN due to its enhanced critical magnetic field, and we pattern the resonators with a lattice of artificial pinning sites to protect the resonator from resistive losses due to Abrikosov vortices. The van der Waals pickup method is used to encapsulate monolayer graphene (G) between two hexagonal boron nitride (hBN) flakes and deposit it between the pre-fabricated capacitors plates (Fig. 1b), before contacting the hBN/G/hBN stack by dry etching and sputtering MoRe. In this work, we present results from two graphene JJ transmon devices, with slightly different fabrication techniques. Device A uses a Ti/Au gate stack deposited directly on the hBN, before the junction is shaped via dry etching. Device B is shaped (Fig. 1c) before a Ti/Au gate stack with a SiN\(_x\) interlayer is deposited (Fig. 1d).

Dispersive Fabry–Perot oscillations. We begin by performing spectroscopy of the resonator in device A as a function of the input power \( P_{\text{in}} \) (Fig. 2a). Varying the resonator’s photon occupation from \( n_{\text{ph}} \approx 1000 \) to \( n_{\text{ph}} = 1 \) we observe a dispersive shift \( \chi = f_J - f_{\text{bare}} \) in the resonator frequency \( f_J \) from the high power value \( f_{\text{bare}} \). This occurs due to a Jaynes-Cummings type interaction between the resonator readout and the anharmonic transmon spectrum, with the anharmonicity provided by the Josephson junction. The magnitude of the shift \( \chi = g^2/\Delta \) depends on the transmon-resonator coupling \( g \), and the difference \( \Delta = f_J - f_g \) between \( f_J \) and the ground state to first excited state transition frequency \( f_g = E_g/\hbar \approx \sqrt{8E_J E_C}/\hbar \), allowing us to infer \( E_g \) from \( \chi \). Studying \( \chi \) as a function of gate voltage \( V_G \) reveals the characteristic band dispersion of graphene (Fig. 2b) and allows the voltage at the charge neutrality point (CNP) \( V_{\text{CNP}} \) to be identified. At negative \( V_G = V_{\text{CNP}} \), the chemical potential \( \mu \) is below the CNP and the graphene is in the p-regime where holes are the dominant charge carrier. Deep into the p-regime, the high carrier density \( n_c \) gives a large \( E_h \) placing \( f_J \) above the resonator and giving \( \chi \) a small negative value (Fig. 2c). As \( V_G \) approaches the CNP, the Dirac dispersion minimises the density of states reducing \( E_h \) and \( f_J \) to a minimum. Since \( \chi = g^2/\Delta \), as \( \Delta \) approaches zero, \( \gamma \) diverges. Once on resonance, the resonator acquires some characteristic of the qubit, significantly broadening the lineshape. Simultaneously, the critical photon number \( n_{\text{crit}} = \Delta^2/4g^2 \) collapses, moving the measurement into the ‘transitional’ regime between high and low photon number as in Fig. 2a, causing the anomalous lineshapes visible in Fig. 2c near CNP. As \( V_G \) is increased past the CNP, \( n_{\text{crit}} \) and the lineshapes recover, with electrons becoming the dominant charge carrier and \( E_h \) increasing to a maximum as expected from removal of the n-p-n junction formed by the contacts. The p-regime also experiences periodic fluctuations in \( E_h \) as a function of \( V_G \) due to coherent electron interference effects in a Fabry–Perot cavity formed by n-p interfaces at the MoRe contacts. Extracting a line

![Image](https://example.com/image1.png)


**Insensitivity to applied parallel magnetic field.** In device B we observe additional coherent electronic interference effects in the form of universal conductance fluctuations (UCF)\(^{14,27}\). As we move from the p to the CNP regime, \(\chi\) is seen to diverge repeatedly as \(f_I\) anti-crosses multiple times with \(f_i\) (Fig. 3a). This behaviour is repeated moving from the CNP to the n-regime, where \(E_j\) is again maximised. We demonstrate the field compatibility of the junction by applying a magnetic field \(B_{||}\) along the length of the junction contacts, parallel to the plane of the film, using the resonator as a sensor for field alignment (see Supplementary Figs. 1 and 2 for alignment procedure details). Monitoring \(\chi\) as \(B_{||}\) is varied between 0 and 1 T (Fig. 3b) and calculating \(f_i\) (using \(g = 43 \text{ MHz}\), extracted from measurements in Fig. 4), demonstrates that \(\chi\) and thus \(E_j\) are not significantly affected by the applied \(B_{||}\). The small amount of variation observed is attributed to charge noise induced gate drift which was observed throughout the duration of the experiment. Studying \(\chi\) as a function of \(V_G\) at \(B_{||} = 1\) T (Fig. 3c) again reveals the characteristic Dirac dispersion as seen in Fig. 3a, with modified UCF and shifted \(V_CNP\) due to slow gate drift. The insensitivity of \(f_i\) to applied field and similarity of device operation at \(B_{||} = 0\) and 1 T confirm the field resilience of both the graphene JJ and superconducting circuit.

**Two tone spectroscopy in high parallel magnetic fields.** In order to better understand the microwave excitation spectra of our system we proceed to measure it directly via two-tone spectroscopy\(^1\). The readout tone is set to \(f_i\) whilst a second tone \(f_q\) is used to drive the circuit. Excitation of the system results in a state dependent shift of the resonator frequency, and is detected by \(\Delta\) (black diamonds) versus \(V_CNP\) (mV) (Fig. 4a) can be fitted with a Lorentzian to extract the transmon transition \(f_i \sim 5.2 \text{ GHz}\) and transition linewidth \(\gamma \sim 400 \text{ MHz}\). At \(B_{||} = 1\) T, \(f_i\) and thus \(E_j\) differ only slightly with \(\gamma\) increasing slightly from 350 to 425 MHz. The transmon resonator coupling \(g = \sqrt{\chi \Delta} = 43 \text{ MHz}\) is extracted from the observed dispersive shift \(\chi\) and detuning \(\Delta\), and used in the calculation of \(f_i\) in Fig. 3. We attribute the change in \(f_i\) from Fig. 3b and the large \(\gamma\) to the dielectric induced charge noise mentioned previously. An estimate of \(E_j = 40.2 \mu\text{eV} = 9.72 \text{ GHz}\) can be provided using the relation \(E_j = \hbar f_i \approx \sqrt{8\epsilon E_C}\). Performing two-tone spectroscopy in the n-regime while tuning \(V_CNP\) reveals a gate-tunable energy level that is visible above and below the resonator (Fig. 4b, \(V_CNP\).
not specified due to gate drift during measurement) that can be fitted to extract $f_1$ and $\gamma$, giving a minimum linewidth of 166 MHz (see Supplementary Fig. 3 for the raw data).

Discussion

The observation of a transition and the inferred high value of $E_J$ in the n and p-regimes (Fig. 4a) provides additional confirmation of the electron-hole symmetry expected in graphene. Additional measurement of the higher order two-photon $f_\nu$ transition would allow for exact measurements of $E_J$ and $E_C$ via diagonalisation of the Hamiltonian, enabling investigations into mesoscopic effects of interest in graphene $J$s. Importantly, the transition and thus $E_J$ can be varied over a wide frequency range, satisfying a key requirement for implementation into topological QC proposals. If graphene based transmons are to be successfully implemented into these proposals however, the large linewidths that currently limit their performance must be reduced. We believe that material improvements due to gate drift during measurement) that can be fitted to extract $f_1$ and $\gamma$, giving a minimum linewidth of 166 MHz (see Supplementary Fig. 3 for the raw data).

Methods

Sample fabrication. To fabricate the two devices (A and B) 20 nm of NbTiN is sputtered onto intrinsic Si wafers in an Ar/N atmosphere. The resonators, feedline and transmon are reactive ion etched in an SF$_6$/O$_2$ atmosphere. In this etching step, an array of artificial pinning sites is also defined. Monolayer graphene is encapsulated between two hBN flakes ($\approx 15$ nm each), then deposited between pre-fabricated capacitors using a PMMA based van der Waals pickup method. Contact to the graphene stack is made by etching in a CHF$_3$/O$_2$ environment, followed by sputtering MoRe ($t \approx 80$ nm). As shown in Supplementary Fig. 4, device A was contacted to give a junction length of 300 nm. A Ti/Au top gate is then sputtered on top of the stack. The device is then shaped in a CHF$_3$/O$_2$ plasma to be 1000 $\times$ 300 nm$^2$ in size. Device B was contacted to provide a junction length of 300 nm. The long thin leads were geometrically restricted in two dimensions, making it less favourable for vortices to form, protecting the superconductivity of the contacts proximitising the junction. The junction is then shaped in a CHF$_3$/O$_2$ plasma to be 500 $\times$ 500 nm$^2$. A SiN/Ti/Au top gate stack is then sputtered to give full junction coverage, giving greater control of $\mu$ in the junction.

Sample characterisation. All measurements were performed in a dilution refrigerator with a base temperature of 15 mK. The samples were enclosed in a light tight copper box, and thermally anchored to the mixing chamber. An external magnetic field is applied to the sample using a 3-axis vector magnet. The two different measurement configurations used in this manuscript are depicted in Supplementary Fig. 5. Two coaxial lines and one DC line were used to control the sample. The sample was connected to the DC voltage source by a line that was thermally anchored at each stage and heavily filtered at the mixing chamber by low frequency RC, $\pi$ and copper powder filters. The line used to drive the feedline input was heavily attenuated to reduce noise and thermal excitation of the cavity, allowing the single photon cavity occupancy to be reached. The output line of the feedline was connected to an isolator (Quinstar QCI-080090XL000) and circulator (Quinstar QCY-06040CM00) in series to shield the sample from thermal radiation from the HEMT amplifier (Low Noise Factory LNF-LN4A-8_C) on the 4 K stage. Resonator spectroscopy of device A was performed using circuit (a) to measure the amplitude and phase response of the complex transmission $S_{21}$ as the frequency was varied. Resonator and two-tone spectroscopy of device B was performed using circuit (b), with a splitter used to combine the readout and excitation tones. This allows the complex $S_{21}$ to be measured, but only at fixed resonator readout frequency otherwise only $|S_{21}|$ can be recorded.

Data availability

The data used to support this study, and the code used to generate the figures are available from a public data repository here https://doi.org/10.4121/uuid:b7340d11-e47e-44eb-a60d-679d758c7160. (ref. 31).

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Author contributions
K.W. and T.T. grew the hBN crystals, J.G.K. and W.U. fabricated the devices, J.G.K., K.L. v.d.E. and D.d.J performed the measurements and J.G.K. and K.L.v.d.E. analysed the measurements. The manuscript was prepared by J.G.K. with K.L.v.d.E., S.G., M.C.C. and L.P.K. providing input. S.G., M.C.C. and L.P.K. supervised the project.

Additional information
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