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Electrically Tunable Coupling of a Ge/Si Core/Shell Nanowire Double Quantum to a Superconducting Transmission Line Cavity

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Abstract

Searching of quantum systems with eliminating decoherence sources is a key to implementing the practical quantum information processing. Ge/Si core/shell nanowire (NW) is predicted as a promising platform to host spin qubits as it possesses strong spin-orbit interaction and lacks of nuclear spins enabling the fast all electrical spin manipulation and long spin coherence times. We demonstrate a hybrid architecture consisting of a Ge/Si NW double quantum dot (QD) capacitively coupled to a superconducting transmission line resonator, which can play a role as the "quantum bus" bridging possible entanglements between spatially separated qubits in future quantum processors. Upon the formation of QDs in segmented NW induced by local electrical gating, the variations of charge states and tunnel couplings modulated by the electric field are manifested from the microwave resonance response. The interaction strength of a photon and a charge qubit is evaluated to be up to ~80MHz through the so-call dispersive readout. The strong coupling regime indicative of the case that the periodic photon absorption/emission by the two-level system is faster than the quantum system decays is not observed perhaps due to the presence of the large decoherence rate estimated to be about several GHz, which can be notably reduced in a near-isolated QD by breaking the links to the reservoirs with increased contact barriers. Our work hints the possible coherent and controllable interaction of a single charge or spin with the trapped photons worthwhile exploring on a well-confined Ge/Si core/shell NW QD.

1. Introduction

Circuit quantum electrodynamics (cQED) is proposed to promote the long distance quantum entanglement. A hybrid cQED with a wide diversity of quantum systems will merge the strengths of each to create a practical quantum processor. Single charge or spin confined in quantum dot (QD) is a promising building block to establish a two-level system (TLS) for quantum information processing. Recently, a strong coupling of the circuit cavity with single electron or spin has been demonstrated in various QD devices including carbon nanotube, gate confined silicon and GaAs double QDs, where the qubit-photon coupling strength exceeds the hybrid system decay rates[1-4]. Here we present the control of the interaction between the photons trapped in a superconducting coplanar transmission line resonator and an individual hole. The holes are confined in a Ge/Si NW with local electrical gating. The coupling strength is up to 80MHz. The qubit energy spacing can be tuned matching to the single mode photon mode enabling the resonant photon absorption and emission. The strong coupling regime is not observed perhaps due to the large qubit decoherence rate.

2. Results

Figure 1(a) shows a photograph of a typical superconducting one-dimensional stripe line resonator made of 150nm thick MoRe film. The signal line is designed with 50Ω impedance ensuring efficient microwave transmission. Ge/Si nanowires are accurately placed closed to the antinodes of the cavity assisted with a supporting polymer film and a home-made micromanipulator. The details of NW transfer has been described elsewhere [5-6]. The nanowires are placing on a set of predefined fine gates with a pitch of 100nm those are covered by a hBN thin flake (8~15nm) as shown in figure 1(b). QDs are formed in the NW by local electrical gating. The device consists of a pair of Ge/Si nanowire QDs. The present work focuses on the interaction of a single double QD with the single mode microwave photons.

Figure 1(d) presents a transmission resonance spectrum when QD is uncoupled to the cavity. The central frequency of resonance is $f_0 = 5.9675$GHz with a line width of 1MHz, indicating the lifetime of trapped photon is around 200ns. The transmission of cavity as a function of drive frequency f_d, taking into account the photon-qubit interaction described by Janys-Cummings model reads[7-8]:

$$T = \frac{-i\sqrt{\kappa_1\kappa_2}}{(f_d - f_0) - \frac{i(\kappa_1+\kappa_2+\kappa_{in})}{2} + g_{eff}\chi} \quad (1)$$

χ is the double QD susceptibly to the microwave field controlled by external electric gating. g_{eff} is the effective dipole-photon coupling strength. Qubit decoherence rate γ hinders the coherent QD-photon interaction. Thanks to the high quality factor of the resonance, the change of single charge in the double QD can be detected from the variation of magnitude and phase due to the presence of the qubit-photon interaction as plotted in figure 1(e) and (f).

Figure 2 shows the evolution of the resonance signal as the tunneling rate t_c of QD at the same charge state is tuned by barrier gate voltage, V_B. With reducing tunneling barrier (decreasing V_B as denoted in figure 2(a), (d) and (g)) between the dots the phase shift changes from positive to negative. The resonance frequency shift and the peaking broadening is extracted as the charge qubit detuning energy is varied with the gates sweeping across the interdot line along the arrows. Fitting from Eq. (1) the qubit-cavity coupling strength g_0 were extracted to be around 80MHz. t_c increased from 4.3GHz to 27GHz with decreasing V_B, in consistent with the sign change of phase shift. The qubit decoherence rate γ is about 15GHz, which is one main reason to block the strong coupling between qubit and photon.

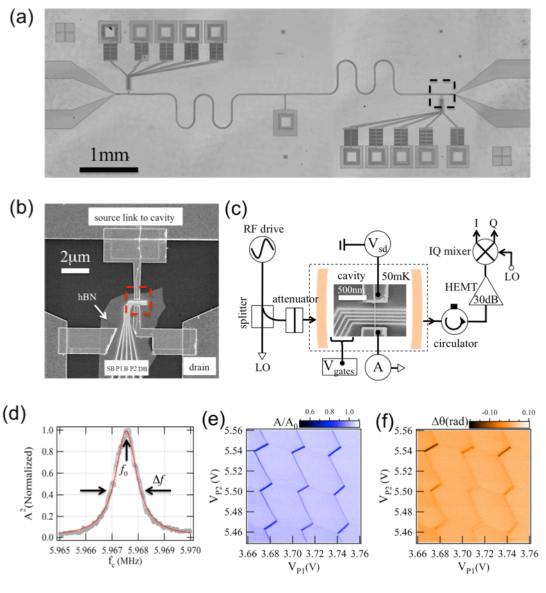

Fig. 1 (a) Photograph in gray scale of a hybrid structure consisting of a one-dimensional transmission line resonator capacitively coupled to a nanowire QD device. (b) Scanning electron microscopy (SEM) image of Ge/Si nanowire device placing on a hBN thin film close to one antinode of the cavity respected to the black dash line frame in (a). (c) A circuit schematic of the measurement setup. QD is formed in the nanowire with a set of 100nm pitch bottom gates as shown by a high magnification SEM image corresponding to the red dash line squre. (d) A typical transmission resonance spectrum of the cavity when QD is uncoupled. (e) Magnitude and (f) phase response of the resonator as a function of plunger gate voltages. The honeycomb patterns in both plots represent the typical charge stability diagram of a double QD.

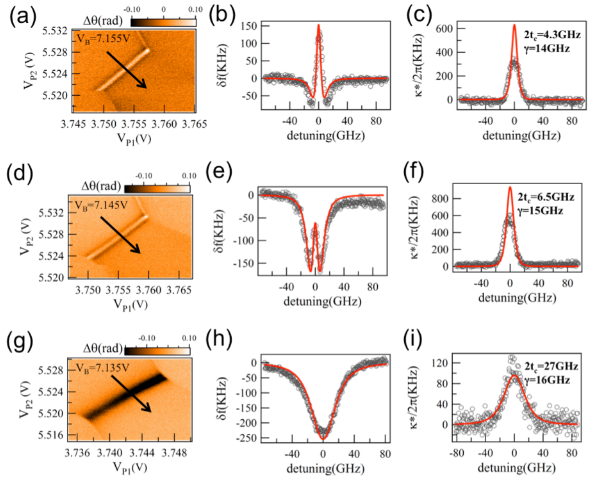

Fig. 2 Evolution of resonance response with varied charge qubit tunnel coupling controlled by the barrier gate voltage, V_B. (a), (d) and (g) show the plots of the phase shifts with QD at the same charge state with V_B = 7.155V, 7.145V, and 7.135V respectively. The black arrows indicate the vector scans of the plunger gate voltages, which alter the detuning energy of the charge qubit. (b), (e), (h) Resonance frequency shifts and (c), (f), (i) changes of resonance line width as a function of qubit detuning energy with V_B respected to (a), (d), (g). The measurement condition is V_{SB}=4.3V, V_{DB}=3.5V, and V_{sd}=0.

3. Conclusions

A Ge/Si nanowire double quantum dot is embedded in to a superconducting strip line resonator with a qubit-photon coupling strength of about 80MHz. With electric gating the qubit energy level spacing can be tuned matching to the microwave cavity mode, enabling the control of resonant photon absorption-emission. The strong coupling regime is not observed, perhaps mainly due to the large qubit decoherence rate.

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