Coupling a quantum dot, fermionic leads and a microwave cavity on-chip : EPAPS.

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I. DETAILS ON FABRICATION AND MEASUREMENT SETUP

The devices are fabricated between the central conductor and the ground plane of a coplanar wave guide (CPW) cavity made out of a Nb(150nm)/Pt(25nm) bilayer. The Nb(150nm)/Pt(25nm) layers are evaporated in a UHV system (base pressure $10^{-9} mbar$ on a highly resistive Si substrate (resistivity $\approx 10k\Omega.cm$)). The fundamental mode of the resonator is about 5 GHz. The SWNTs are grown using a standard CH_4 recipe after the reactive ion etching process which allows us to define the CPW cavity. They grow from catalyst particles placed at an anti-node of the electric field of the fundamental mode of the resonator. The critical temperature of the Nb/Pt bilayer is reduced from 8.9K to 8.7K during this process. After this process, suitable SWNTs are localized and contacted with 70 nm-thick Pd layers using standard electron beam lithography. Four devices are connected at the same time inside a cavity. The DC lines are implemented by "opening" the ground plane with 50Ω AC shunted lines. The coupling capacitances used to inject photons in the cavity are of finger type. After the growth, we obtain quality factors in the 200-1000 range. These low values are due to residual imperfections in the lithography of the resonators and the high coupling capacitances Cin(out) of about 4 fF which limit the quality factor to about 8000 for the empty resonators.

The high frequency measurements are performed with an amplification chain with room temperature microwave amplifiers operating in the 4-8GHz range. The input and output of the cavity shown in figure 1a are wire bonded to 50Ω Au CPW lines made on a printed circuit board. The overall gain is $83dB$ as shown in figure 1c of the main text. The input power of the microwave signal is -60dBm which yields an average number of photons of about 10000 in the cavity. Such a power ensures the linear regime for the AC excitation. At the temperature of the experiment 1.5K, the thermal population of the mode at 4.976 GHz is 5.8. We use a heterodyne detection scheme with a frequency modulation of $977Hz$. For the colorscale plots, the phase of the measured signal is calibrated before each V_{sd} scan at constant V_g using the "off" point as reference. In addition to the high frequency measurement, the standard lock-in detection technique with a low frequency modulation of 77.7Hz is used to measure the DC differential conductance.

II. FREQUENCY DEPENDENCE OF AMPLITUDE AND PHASE.

We present in in figure 2a the raw data for the amplitude and phase versus frequency for the resonator used in the main text. The phase displays qualitatively the expected variations for a single resonance centered at $4.976GHz$ and a quality factor of 160, represented in red line. The amplitude displays a more complex anti-resonance which is not important in our case since we focus on the phase in our measurements. The observed 'wiggles' in both curves are due to imperfections of our amplification lines. Subtracting the background by taking a reference "off" point as explained in the main text allows us to get rid of most of them.

As shown in figure 2b, microwave simulations indicate that the direction of the electric field is disturbed on the "side-edges" of the wires but weakly in the vicinity of the nanotube dot where the edges of the wires face the central conductor. Another important concern is whether the wires which are metallic limit the quality factor of the mode (we have simulated the effect of a single wire for the sake of simplicity). Simulations also show that the quality factor of the resonator is reduced only by several percents when the total quality factor is lower than 10^5. This leads us to attribute our modest quality factors to residual lithography imperfections which can be reduced easily in principle.

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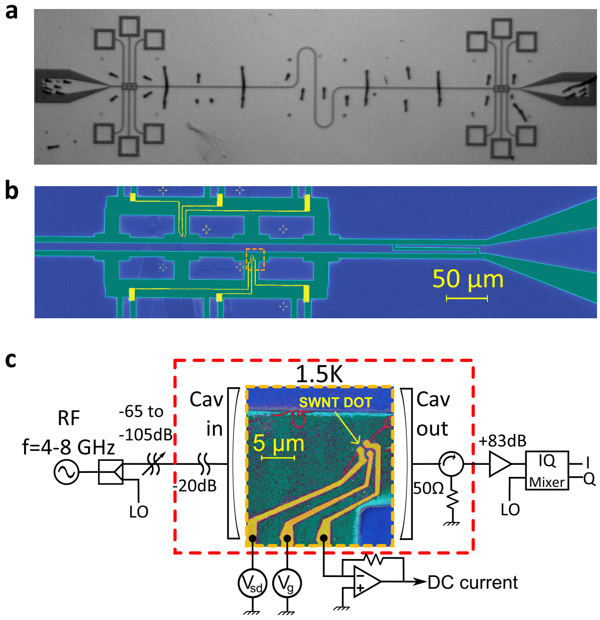

FIG. 1: a. Photograph of our CPW cavity on a wide scale. At each anti-node of the electric field of the fundamental mode, SWNTs are grown in order to make our devices. b. Zoom on one zone of device fabrication, close to one of the two coupling "finger" capacitances. c. Zoom on a typical device and details of the measurement setup.

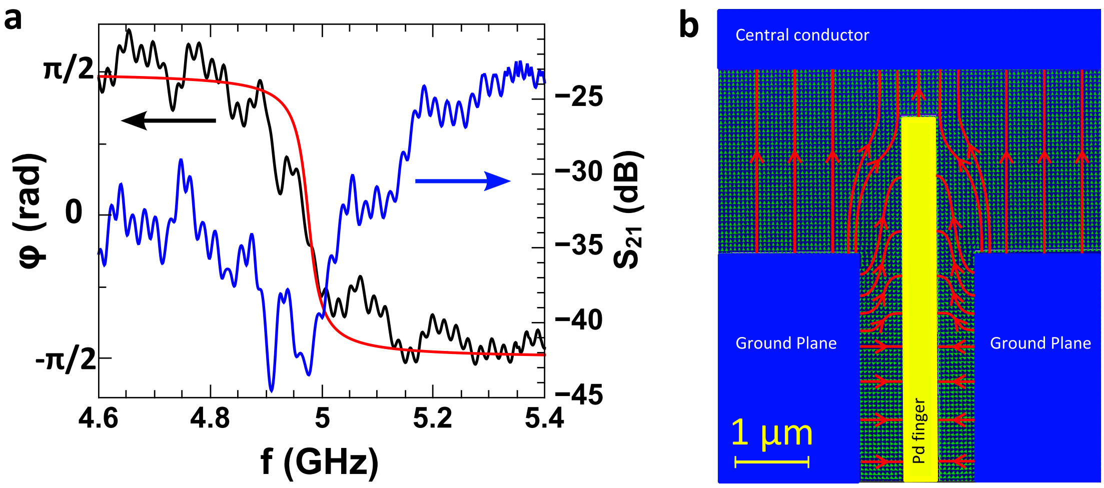

FIG. 2: a. Raw data for amplitude and phase of the resonator presented in the main text. b. Qualitative variation of the electric field lines inside the gap of the cavity, in presence of a Pd finger.