A superconducting resonator designed for coupling to spin based qubits in quantum dots

G Allison\textsuperscript{1,2}, A Oiwa\textsuperscript{1,3}, S Kumar\textsuperscript{4}, D DiVincenzo\textsuperscript{4}, M Ketchen\textsuperscript{4}, K Hirakawa\textsuperscript{3,5,6}, H Takayanagi\textsuperscript{7} and S Tarucha\textsuperscript{1,6}

\textsuperscript{1}Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
\textsuperscript{2}Department of Physics, Princeton University, Princeton, NJ 08544, USA
\textsuperscript{3}JST CREST, 4-1-8 Hon-cho, Kawaguchi-shi, Saitama 332-0012, Japan
\textsuperscript{4}IBM T. J. Watson Research Center, Yorktown Heights, NY 10598, USA
\textsuperscript{5}IIS, The University of Tokyo,4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
\textsuperscript{6}INQIE, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
\textsuperscript{7}Department of Physics, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
giles@meso.t.u-tokyo.ac.uk

Abstract. We present the implementation of a system for the quantum state transfer between electron spin and photons exploiting the coupling of an InAs self-assembled quantum dot to a superconducting resonator cavity.

1. Introduction
Manipulation of the electron spin in a quantum dot has long been proposed as a suitable candidate for a quantum bit (qubit) due to the long spin coherence times involved [1]. However, electron spin is an unsuitable property for long distance interactions between qubits, thus, for any large scale quantum computing network, it is necessary to transfer information between different quantum states. In previous studies, several types of two-level systems, such as superconducting plasmons and transmons [2-4], have been coupled to the discrete photon modes in high quality resonators. This has lead to the recent demonstration of a two qubit superconducting processor and implementation of quantum search algorithms [5]. Microcavity systems [6] and photonic crystals [7] coupled to the exciton states of a quantum dot have also been demonstrated in the strong coupling regime. In this work we propose a system for the quantum state transfer between electron spin and photons exploiting the coupling of an InAs self-assembled quantum dot (SAQD) to a resonator cavity [8]. The integral part of our device is the strong spin-orbit interaction (SOI) of InAs SAQDs, which realizes the coupling between the photon field and electron spin in the cavity [9]. The spin coherence times of InAs based SAQDs are longer than that of superconducting qubits [10-11].

In this work we present fabrication methods and characterization measurements of quarter-wavelength coplanar waveguide superconducting resonators coupled to SAQDs. Niobium is deposited using a sputtering method onto a GaAs substrate and high q-factor resonators are patterned using electron beam lithography (EBL) and reactive ion etching (RIE) techniques. A novel method has been devised to protect SAQDs on the surface of the GaAs during fabrication and for accurate positioning such that a single SAQD is sufficiently close to an antinode of the first harmonic standing wave of the...
cavity. The magnitude of the SOI in such InAs SAQDs is large (~100 µeV [12]) resulting in an
electron Landé g-factor of 4-5, thus, a small magnetic field, B~0.1 T, brings into resonance with the
bare frequency of the resonator \(f_0=5-7\) GHz where vacuum Rabi splitting is observed and qubit-
cavity coupling strength determined.

2. Background
Theoretical studies of electron spins in nanowire quantum dots placed within transmission line
resonators have revealed possible coherent manipulation, storage and readout of quantum information
due to the spin-orbit interaction [9]. This all electrical system has the possibility of coupling quantum
dot spins in different quantum dots through the resonator modes. InAs self-assembled quantum dots
should show a similar behaviour and have a great advantage due to their large spin-orbit interaction. In
[9] it is shown that the Jaynes-Cummings [13] coupling of this system is given by

\[
M = \frac{0.25eEH}{\Delta E_0} \frac{L}{\lambda_{SO}}
\]

where \(e\) is the electron charge, \(H\) and \(L\) are the height and length of the SAQD respectively, \(E_0\) the
Zeeman energy, \(\Delta E_0\) the energy level, and \(\lambda_{SO}\) the spin orbit coupling length. \(E\) is the effective electric
field in the cavity. SAQDs with \(L\sim200\)nm have been shown to have Landé g-factor 3-8 [14], therefore
a magnetic field of \(B~0.1T\) is required to bring the dot to the resonant frequency of 5-7 GHz. The
strong spin orbit coupling \(\Delta_{SO} \sim 150\) µeV [12] results in a coupling of \(M=0.3-4\) MHz. The coupling
constant value, however, can be widely altered by the choices of the QD parameters.

3. Sample fabrication & measurement method
The uncapped SAQDs are grown on an insulating GaAs substrate and are randomly positioned with
varying size up to a length of ~300nm and height ~40nm [15]. The first stage of the sample fabrication
uses atomic force microscopy to find a SAQD of suitable size. Secondly, EBL techniques are used to
deposit a thin (100nm) film of SiO\(_2\) which covers just the SAQD of interest and will act as an
insulating buffer layer in the latter processing stages. Next, all the unwanted SAQDs are removed
using an H\(_2\)SO\(_4\):H\(_2\)O (1:5) etch for a few seconds. A thin (200nm) layer of Niobium is then deposited
on the sample surface using a sputtering technique before EBL and RIE techniques are used to form
the transmission line and quarter wavelength resonators.

There are two factors crucial to the performance of the device; firstly the resonator must be
accurately positioned so that the SAQD lies in the resonator cavity close to an antinode of the first
harmonic, and secondly, the RIE rate and film thickness must be accurately determined to ensure that
the SAQD is not damaged during this process.

Ten quarter wavelength resonators of width 6µm and different lengths, and thus different resonant
frequencies, of the order 4mm are capacitively coupled to a superconducting feedline and in turn each
resonator is coupled to a SAQD. A gate electrode is added to give independent control of the electron
number and state. A schematic of the resonator design is shown in figure 1. The transmission through
the feedline is measured as a function of frequency by a vector network analyser (Agilent model
E5071C) and a dip in the transmission is observed at the resonant frequency of each resonator.
Cryogenic amplifiers and attenuators are used to control the RF power as shown in figure 2 and the
sample is cooled to \(T\sim 50\)mK using a dilution refrigerator placed within a superconducting magnet.

In the work presented here we measure the properties of a superconducting Nb resonator fabricated
using these techniques, however, this device currently contains no SAQDs. The purpose of these tests
is to check the quality, power and magnetic field dependence of our resonators to ensure the feasibility
of the proposal for quantum state transfer.
4. Results

High quality factor resonators are required in order to reach the strong coupling regime, thus it is extremely important that our fabrication techniques result in a good quality resonator. In this section we show characterisation measurements of our resonators at low power and low temperature. The resonances have quality factor of the order 3,000 (estimated from the full width at half height, a more accurate fit can be obtained using [16]). The resonances were observed at powers below -100dBm, the power at which the single photon excitation condition is reached (see figure 3).

The resonances were measured as a function of magnetic field as shown in figure 4. The resonant frequency decreases weakly with magnetic field for B<0.15T, which is followed by a fairly rapid decrease before disappearing altogether at B~0.25T. The origin of the rapid disappearance of the resonance is likely to be due to kinetic inductance [17]. For a SAQD with a g-factor of 3-5 we expect coupling at B~0.1T, well below this critical field. It should be noted that the disappearance of the resonances is not due to the loss of superconductivity of the Nb; in separate measurements of the dc transport of a device with the same geometry as a typical resonator, the superconducting behaviour is observed in fields as large as B=3T. The data show a non-monotonic background due to reflections in...
the transmission line, however, in figure 4 this background has been removed to a good approximation by subtracting the high magnetic field data.

5. Conclusion
We have proposed a system for the quantum state transfer between photons and electron spins. In our preliminary measurements we have shown that our resonator devices work in the magnetic field range required for the Zeeman energy of a SAQD to equal the resonant energy of the device. We have also shown that the quality factor is sufficient to produce a measurable coupling between dot and resonator. The next stage is to implement the SAQD into the device and to measure the coupling strength between dot and resonator.

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