Supplementary Material for "Electron-spin-resonance meanderlines for effective spin control in Si quantum dots for large-scale qubit applications"

Yao-Chun Chang,[1] Ian Huang,[2] Chiung-Yu Chen,[2] Min-Jui Lin,[3] Shih-Yuan Chen,[2,3,a)] and Jiun-Yun Li[1,3,4,a)]
[1)]*Graduate Institute of Electronics Engineering, National Taiwan University, Taipei 10617, Taiwan*
[2)]*Graduate Institute of Communication Engineering, National Taiwan University, Taipei 10617, Taiwan*
[3)]*Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan*
[4)]*Taiwan Semiconductor Research Institute, Hsin-Chu 300091, Taiwan*

BALANCED-TO-UNBALANCED (BALUN) CONVERTER

In order to measure reflection coefficients (S_{11}) of ESR meanderlines, microwave signals generated by the vector network analyzer (VNA) are fed through coaxial cables and RF probes to the device. It then is reflected back to the source due to the impedance mismatch. While coaxial cables and RF probes in a ground-signal-ground (GSG) configuration are unbalanced

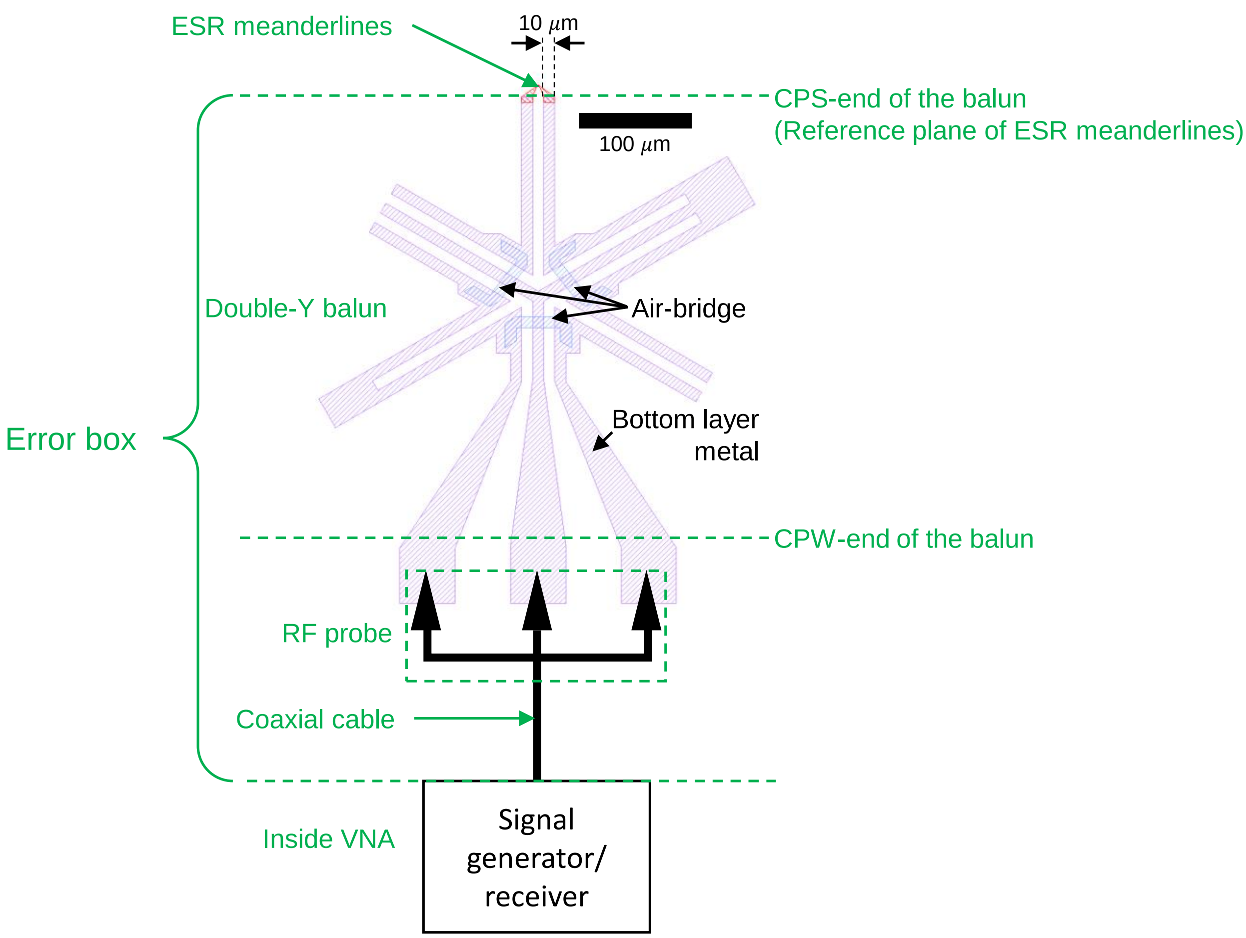

FIG. S1. Top view of ESR menaderlines and baluns for on-wafer microwave measurements.

[a)]Authors to whom correspondence should be addressed: shihyuan@ntu.edu.tw and jiunyun@ntu.edu.tw

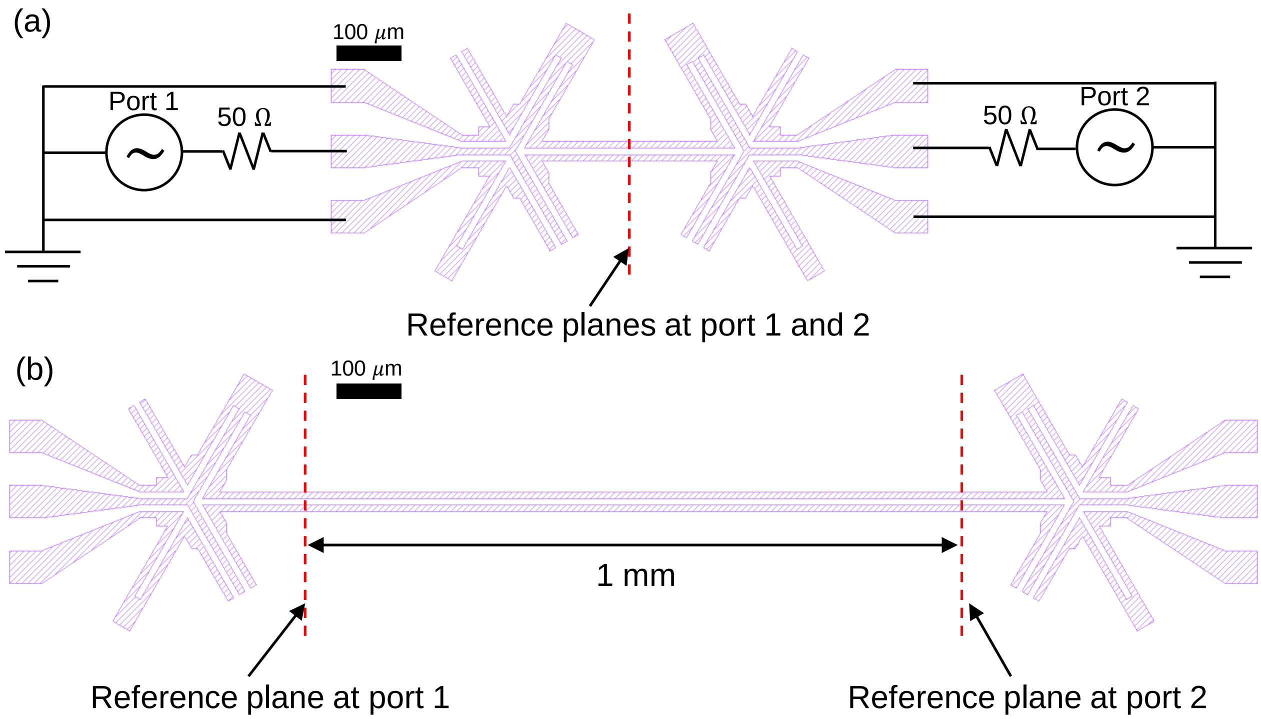

FIG. S2. (a) Thru and (b) Line connection. The signal generator and the 50 Ω impedance inside are shown.

lines, coplanar strips (CPS) and twin lines are balanced lines. RF signals are fed into the ESR meanderlines via the CPS. Thus, a microwave component, balanced-to-unbalanced (balun) converter, is required for a low-loss transition between RF probes and ESR meanderlines. A double-Y balun[1] enables a low-loss transition between unbalanced coplanar waveguides (CPW) and balanced CPS. The CPW-end of the balun is contacted by the RF probe, while the CPS-end is connected to the ESR meanderlines (Fig. S1). Air-bridges pass above the SiO_2 layer that covers the ESR meanderlines and the QD gates [Fig. 1(c) in the main article] to connect to the ground conductors and are necessary for the operation of the double-Y balun.

THRU-REFLECT-LINE (TRL) CALIBRATION

The goal of the characterization of ESR meanderlines is to measure the reflection coefficients. The reflection coefficients depend on the choice of the reference plane, which is an imaginary plane where the reflected waves are measured. We chose the reference plane of ESR meanderlines at the cut-plane where the CPS line width tapers to 10 μm, which is depicted as the CPS-end of the balun in Fig. S1. In order to obtain the reflection coefficients of meanderlines, it is necessary to connect the reference plane to the vector network analyzer (VNA) by coaxial cables and RF probes. In our experimental setup, the VNA we used is an Agilent E8361C PNA network analyzer, the transmission lines are Gore PhaseFlex 2Z0AJ0AK0480 coaxial cables, and the RF probes are MPI Titan RC probes with a 100-μm probe pitch. Calibration techniques are then applied to eliminate the attenuation, and the phase shift contributed by the error box, i.e., the total signal path between the reference plane and the signal generator/receiver (Fig. S1). Thru-Reflect-Line (TRL) technique is a calibration procedure to characterize the error box by mathematically manipulating the scattering parameters of three specific connections – Thru, Reflect, and Line[2]. Details on the mathematics of TRL calibration are provided in 3. In our experimental setup, the Thru connection consists of two baluns connected back-to-back with their CPS-ends, as shown in Fig. S2(a). The Line connection is similar to Thru, but with a 1-mm CPS delay line inserted between the two baluns, as shown in Fig. S2(b). The Reflect connection used here is just the ESR meanderline mounted at the CPS-end of the balun (Fig. S1). The reflection coefficients of the load in the Reflect connection are a by-product of the calibration procedure[3].

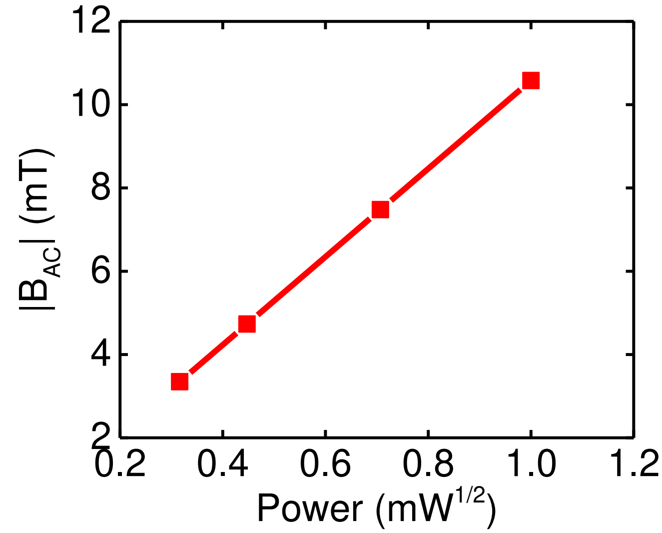

FIG. S3. $|B_{AC}|$ at the center QD with different input powers. The simulated structure includes the balun and QD gates with W = 100 nm and S = 360 nm at 30 GHz.

TRANSDUCTION COEFFICIENTS OF MICROWAVE POWER TO MAGNETIC FIELD

The performance of ESR structures could be assessed by the transduction coefficients of microwave power to magnetic field. The magnetic field at the center QD against the input power is plotted in Fig. S3. The transduction coefficient of microwave power to magnetic field is extracted from the slope ($\sim$ 10.6 mT/$\sqrt{\text{mW}}$).

REFERENCES

[1] V. Trifunović and B. Jokanović, IEEE Trans. Microw. Theory Techn. **42**, 1454 (1994).
[2] G. F. Engen and C. A. Hoer, IEEE Trans. Microw. Theory Techn. **27**, 987 (1979).
[3] D. M. Pozar, *Microwave Engineering* (Wiley, New York, 2011).