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Ta Based Damascene Resonators

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***Abstract*— Transmon qubits have become a leading technology in quantum information science (QIS), with fabrication techniques widely accessible. Historically, devices were predominantly made from aluminum (Al) and niobium (Nb), but state-of-the-art transmons now use tantalum (Ta) achieving coherence times up to and exceeding 0.5 milliseconds [1-3]. The differentiation in performance between Ta and Nb-based devices is attributed to the surface oxidation states affecting Two-Level-System (TLS) noise. One approach to quickly evaluating material and device performance consists of fabricating only the readout resonator of a qubit and evaluating the quality factor which is the strategy employed in this project. Our research focuses on Ta coplanar waveguide (CPW) resonators fabricated using a damascene technique producing pristine metal structures within silicon substrates. This approach increases the dielectric substrate's participation ratio while keeping device edges oxide-free due to entrenchment. This collaborative effort, involving Pacific Northwest National Laboratory (PNNL), NY CREATES/SUNY Poly, and Brookhaven National Laboratory (BNL), has resulted in resonators with Q factors as high as 10^4 at low power. Ongoing studies aim to further understand and improve device performance by systematic analysis of oxygen trapped between device layers during processing. This research showcases the potential for significant improvements in superconducting qubit performance via the damascene process, heralding new possibilities for the advancement of scalable QIS technology.**

Keywords—resonator, CPW, tantalum, damascene, CMP

I. Introduction

Improved coherence times in transmon based qubits were observed with changes in materials and surface engineering [1-3]. This is attributed to the oxide thickness and type that contribute to Two-Level-System (TLS) noise in devices fabricated under nominally identical conditions [4, 5]. More recently, measurements focused on the Q-factor of Ta resonators, proxy for qubits, show that the component associated with TLS depends on the surface participation ratio (SPR), the fraction of the electric field energy residing in surface oxides [6]. Here we show recent progress on a different type of resonator fabrication (a damascene process) that embeds the resonator into a crystalline Si substrate.

II. Experimental

A. Device Fabrication

Ta-based superconducting resonators were fabricated by NY CREATES utilizing a damascene process developed by Bhatia, et al. A 300 mm Si (100) wafer was prepared for the damascene process with a deposition of 15 nm SiO_2 followed by 50 nm of SiN. Device geometry and features necessary for chemical mechanical planarization (CMP) were defined by 193 nm optical lithography and etched to the base Si substrate by reactive ion etching (RIE). The exposed Si substrate was further etched with an aqueous hydroxide-based etchant yielding a trench with sloped sidewalls. The SiN layer was removed by hot phosphoric acid, and an ultrathin layer of TaN was deposited via atomic layer deposition (ALD) to begin the damascene process. Next, a Ta thin film was sputtered yielding a crystalline thin film in the alpha phase due to the TaN layer seeding the BCC crystal structure. Ta in the alpha phase possesses the T_c necessary for optimal device performance in the range of 3.2 - 4.3 K as opposed to beta-Ta (tetragonal) yielding T_c in the mK range. In order to remove excess Ta metal, CMP was performed to remove all surface Ta down to the SiO_2 layer leaving only Ta in the trenched Si substrate. Lastly, the SiO_2 layer was removed with buffered oxide etch (BOE) leaving pristine Ta device sidewalls extending a short distance above the Si substrate[7].

B. Device Layout and Modeling

Chips (5x5 mm^2) diced from processed wafers contained a set of quarter wave CPW resonators of varying lengths coupled to a single transmission line in a hanger-type configuration. The eigenfrequencies and coupling quality factors of the resonators were numerically simulated using the RF Module of COMSOL.

C. Measurement

The quality factors for all the resonators on a chip were characterized by S-parameter measurement (S_{21}) in a dilution refrigerator (DR) with a base temperature of 10 mK. Individual chips in enclosures were mounted on the cold finger of the DR and enclosed in a magnetic shield. The input and output of the enclosures were connected to RF infrared (IR) filters and other components on the mixing chamber (MXC) plate via hand formed Sn-plated Cu RF coax cables. On the input side, stainless steel housing attenuators were used at the 50K (0 dB), 4K (-20 dB), and still (-10 dB) plates while Cu-housing attenuators were used at the cold plate (-10 dB) and MXC (-20 dB) plate to thermalize the semi-rigid sCuNi coax signal lines. On the output side, two double circulators with cryo-terminators isolated the resonators from IR originating at warmer stages on the semi-rigid sCuNi coax signal lines. The output signal was amplified at 4K with a high-electron-mobility transistor (HEMT) amplifier yielding a nominally constant 39 dB across the 4 - 8 GHz range and with two room temperature, ultra-wideband amplifiers yielding a nominal 34 dB across the same bandwidth prior to readout by a vector network analyzer. An initial sweep of the S_{21} response was taken from 3 to 8.5 GHz in 10 kHz steps with a 100 Hz intermediate frequency bandwidth for device resonator tone identification. Afterwards, individual resonators were characterized as a function of various powers in temperatures up to 600 mK.

III. Results

Quality factor (Q) along with coupling quality factor (Q_c), phase, and resonance frequency were determined from fits of S_{21} scans using a modified diameter correction method (DCM) model from Khalil, et al [8]. The results of this ongoing project thus far include identification of resonance frequencies in the target range, constant coupling quality factors on the order of 10^4 to 10^6 as a function of temperature and input power, and quality factors on the order of ~10^4.

IV. Discussion

We evaluated superconducting CPW resonators fabricated by a damascene process for quality factor performance. The damascene process developed by NY CREATES possesses an inherent scalable character, and this study demonstrates consistent and predictable performance of damascene Ta CPWs. In our first series of devices, the base TaN layer was exposed to atmosphere during processing leaving oxide of some degree buried in the device trench. The TaN fabrication step has since been modified to minimize the exposure to atmosphere, and we have undertaken analysis of the buried oxide in our first generation of chips in order to compare with our upcoming measurements on the next generation of pristine devices. The completion of this study will build the foundation for damascene resonators to be incorporated as readout resonators in highly scalable qubit systems.

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