

NIRT: Metal-Dielectric Interfaces at the Nanoscale For Quantum-Information and Microwave Devices

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Introduction and Objectives

The importance of understanding and controlling defects at the nanoscale has long been recognized for devices that employ semiconductor-oxide interfaces or semiconductor heterostructures. For example, the exceptionally low density of electrically active defects at the silicon/SiO₂ interface has enabled the wide-spread of use of silicon-based transistors. While defects at interfaces with semiconductors have been studied for over 50 years, the rapidly emerging fields of quantum information and high-frequency communication technologies require a similar understanding of defects in insulators and at the metal/insulator interface. In particular, the further development of quantum computing and quantum communication depends on reducing loss mechanisms to extremely low levels to prevent decoherence, which destroys quantum mechanical entanglement and causes loss of signal.

We address these challenges by employing advanced fabrication techniques that have nanoscale control, as well as new sensitive tools for characterizing and imaging defects in devices. Our vision is an improved understanding of the science of high-quality dielectrics and atomic-scale interfaces that will lead to improvements in the performance of nanoscale devices. A second objective is to utilize the unique defect sensitivity of nanoscale devices to explore the properties of metal-insulator interfaces relevant to a wide range of applications, such as low-loss capacitors for microwave communication devices.

Dielectric Loss in Josephson Junction Quantum Bits

The storage and manipulation of information in quantum mechanical states has recently been proposed as a powerful new method for computation. Although quantum computers have the promise of giving exponential speedups compared to classical computers, they are also extremely sensitive to defects that allow the quantum states to couple to other unwanted degrees of freedom. Although these defects need to be understood and minimized, they also may be fundamentally studied with unprecedented sensitivity.

Josephson junctions show great promise for experimentally implementing quantum bits (qubits). We have recently shown that a dominant source of decoherence in this system comes from two-level state (TLS) defects in the amorphous insulators (dielectrics) of the system that is used as capacitor elements[2]. The TLS comes from random bonding in amorphous materials, where one bond in 10⁷ to 10⁸ atoms produces a site where an atom can quantum mechanically tunnel between two metastable equilibrium positions. When the tunneling frequency matches that of the qubit, they couple strongly. Although TLS defects have been known for many years, this work represents the first experimental system with enough sensitivity to study individual defects. We have explicitly measured the random distribution of TLS matrix-element couplings, and shown that they agree in detail with theoretical predictions. The magnitude of the coupling also suggests that the dominant source of defects is OH radicals in the insulator. It is interesting to note that a defect density on the order of parts per billion can readily be measured by this technique.

Characterization with Superconducting LC Resonators

A complementary measurement of dielectric quality is possible through the determination of LC resonator loss at microwave frequencies using superconducting inductors and thin film capacitors. Because the energy loss in a superconductor is extremely low, this measurement allows very sensitive determination of losses in a dielectric material. In this research program, we have found surprising non-linear dissipation of dielectric materials at low temperatures, characterized by the decrease in dissipation as the resonator power or temperature is raised. This behavior can be generally understood from the saturation of TLS defects, which then effectively removes the dissipation mechanism. We found that amorphous SiO_x , a common insulating material for superconducting devices, has extremely large loss. With a loss tangent of about 10^{-2} , this measurement explains why qubits made with this material has large decoherence.

Further experiments have investigated the magnitude of the loss for a variety of materials. For phonon loss from TLS defects, previous work has shown that most materials give similar magnitudes of loss. However for electronic loss, we have found that there are significant differences with changes in dielectrics. The material SiN_x has about twenty times lower loss than SiO_x , and amorphous Si:H ten times lower still. This behavior can be qualitatively understood considering the bond coordination of the different materials. As the number of bonds increase from 2 to 3 to 4 in O, N, and Si, the atom is more constrained and its random bonds are less likely to yield two metastable states.

We note that for amorphous Si, the measurement of the TLS defect density is an important characterization for room temperature applications such as transistors and solar cells. We plan to investigate whether low temperature dielectric loss can be used as a new diagnostic for this important technological material.

This discovery of TLS defects was a crucial breakthrough in improving the coherence of Josephson qubits[3]. We have improved the coherence time of Rabi oscillations from 40 ns to 470 ns for a device that was optimized using the fundamental concepts learned in this program. With dramatic improvements in coherence times and amplitudes of the Rabi oscillations, more complex qubit circuits are now within reach. We believe it should be possible to construct a prototype quantum computer with 10 qubits within the next few years.

Single-crystal dielectrics

The TLS defect sites arise mostly from the use of amorphous materials, such as SiO_x and SiN_x , or other oxides such as AlO_x for the tunnel barrier. Improving bond quality, number, and strength all gives rise to lower TLS density and activity, but another approach is to attempt to fabricate single-crystal dielectric materials. This is challenging when design considerations force the use of metal electrodes, but from coplanar stripline resonator (CSR) measurements we know that extremely low loss, and correspondingly very high quality factors, can be achieved at low temperatures. CSR's fabricated on single-crystal sapphire (Al_2O_3) can achieve quality factors well in excess of 10^5 . We therefore plan to pursue fabricating metal-dielectric-metal heterostructures with single crystal dielectrics. Approaches will include (a) MBE growth of single-crystal dielectrics (e.g. Al_2O_3) on single-crystal metal electrodes; (b) wafer bonding single crystal dielectrics to amorphous metal electrodes[4], followed by dielectric patterning and counterelectrode deposition; and (c) explore the use of intrinsically single-crystal metals grown on single-crystal dielectrics and vice versa, focusing on the CoSi_2/Si heterostructure material [5]. Microwave loss of these various material systems will be tested through the fabrication of three-layer LC resonator structures.

Metal-Insulator Interfaces with High-Permittivity/Ferroelectric Materials

Controlling and understanding the metal/insulator interface is also critical in achieving low losses in capacitors for microwave communications. Thin film dielectric materials that exhibit both an electric field-tunable dielectric constant and a low loss tangent provide exciting new opportunities in MIM capacitors for novel frequency agile devices. They are potentially low-cost, can be integrated with conventional IC technology, have intrinsically fast switching speeds, and have better RF power-handling characteristics compared to semiconductor diodes.

High dielectric tunabilities are most effectively achieved by using metal-insulator-metal (MIM) capacitor structures. At microwave frequencies the conductor losses from the bottom electrode are believed to dominate the total device loss. Minimizing the loss contribution from the conductor would not only improve device performance but also facilitate the interpretation of the measured device loss in terms of the dielectric loss, whose precise frequency dependence is often unknown. To reduce the conductor losses, thick metal bottom electrodes with a low electrical resistivity are required. To date, however, most microwave capacitors employ Pt bottom electrodes because of their chemical stability and ability to withstand the high-temperatures and oxidizing conditions during dielectric deposition. In many respects, Au would be the ideal electrode material. Au has a much lower electrical resistivity ($\sim 2 \mu\Omega\text{cm}$) than Pt ($\sim 9.7 \mu\Omega\text{cm}$) and does not oxidize. However, the low melting temperature of Au ($\sim 1064 \text{ }^\circ\text{C}$) combined with the high deposition temperatures required for high-quality crystalline tunable dielectrics ($\sim 600 - 1000 \text{ }^\circ\text{C}$) make it difficult to integrate ferroelectric perovskite films directly with Au bottom electrodes.

In the present project period we have demonstrated that a novel tunable dielectric, bismuth zinc niobate (BZN), can be integrated directly with low-resistivity Au bottom electrodes [6]. The favorable crystallization kinetics of the BZN pyrochlore structure allowed for a low thermal budget process compatible with Au electrodes. BZN thin films on Au bottom electrodes showed very low dielectric loss tangents of ~ 0.0005 and high dielectric tunabilities of $\sim 50\%$. The Au/BZN interface was abrupt and free of reaction phases. At high frequencies ($>1 \text{ MHz}$) the total Au/BZN capacitor device loss was significantly reduced compared to capacitors with Pt bottom electrodes. Furthermore, the low device losses of Au/BZN capacitors revealed an additional, device geometry-dependent loss mechanism that contributed significantly to the device loss at high frequencies. Studies are currently underway to investigate the origin of this loss mechanism.

[1] For further information about this project link to <http://gabriel.physics.ucsb.edu/~martinigroup/#home> or email martinis@physics.ucsb.edu

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