Effect of Oxide Layers on the Performance of Split Ring Resonator Metamaterials

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Abstract

The presence of very thin native oxide layers are shown to have a large effect on the spectral location of the resonance of a split ring resonator design. We show simulation and measurement results illustrating this shift.

1. Introduction

Split ring resonator (SRR) designs are common in the metamaterial community. Oftentimes the simulation and measured results do not align well. While often attributed to fabrication errors in the shape of the SRR, we demonstrate a powerful effect that has not been previously reported: a low refractive index layer separating a high-index substrate from the metal split ring resonator leads to a capacitance that can substantially shift the resonant frequency. A layer as small as 1nm can have a large effect on designs with resonant frequencies in the thermal infrared.

We compare simulations with measured data for SRRs on GaAs with and without the oxide layers. We also look at SRRs on silicon substrates which include a titanium adhesion layer as well as the native oxide layer. These configurations that we compare are shown in Fig. 1.

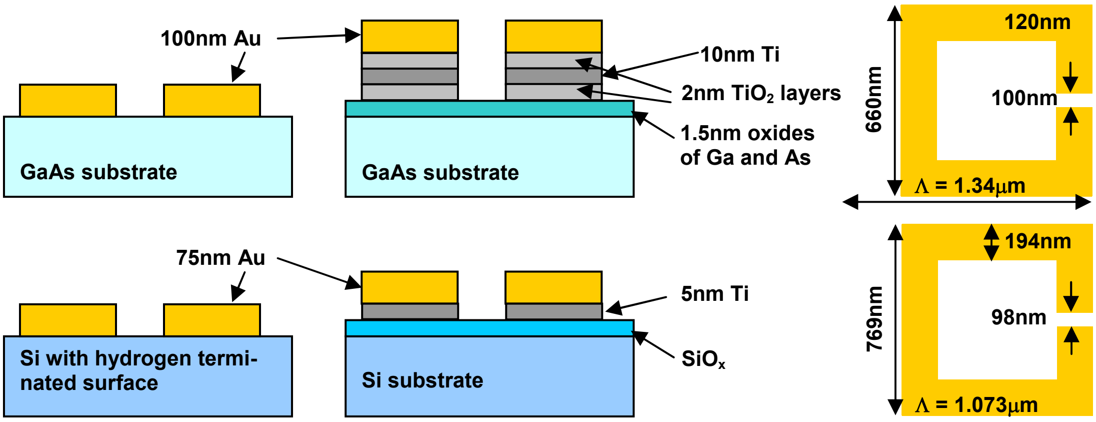

Fig. 1. Side and top views of originally modelled SRR designs (left) and design including the titanium adhesion layer and oxide layers associated with the titanium and substrates (middle). Top view shows dimensions of fabricated parts also used for the simulations.

2. Characterization of GaAs and Ti oxide layers

The physical SRR contains two non-ideal oxide layers, one on each side of the Ti film. The as-received GaAs wafers were characterized using a V.A.S.E. system (J.A. Woollam) and were found to have a native oxide of 1.5nm, as expected.[1] Although this oxide can be easily removed from the bare wafer, attempts to remove the native oxide immediately before metallization damaged the EBL pattern, so the stack was applied on top of the oxide allowing a thin TiO_x layer to form beneath the Ti. Additionally, the system used to deposit the metal has a single power supply, so there was a delay before adding the Au film that resulted in the formation of approximately 2.0nm of TiO_x between the Ti and Au layers.

3. SRRs on Gallium Arsenide Substrate

Inclusion of the aforementioned oxide layers in the simulations illustrates their effect. The simulations are performed using rigorous coupled wave analysis (RCWA). Simulating 110nm of gold directly on GaAs leads to a resonance minimum at 9.3µm as seen in Fig. 2. This does not correspond well to the 8.52µm measured transmission minimum. Fixing the total metal thickness at 100nm, we now change to 100nm of Au and 10nm of Ti directly on GaAs. This combination worsens the agreement, with a minimum at 9.5µm. However, with the addition of the GaAs native oxide layers (1.5nm) and the Ti oxide layers (2nm on either side of the Ti), the simulated minimum shifts to 8.6µm. For the simulation n=1.5 is used for the oxides of GaAs and TiO_2 refractive index values were used for the oxides of Ti.

Measured data is TM transmission through the entire wafer, thus including a second surface. To compare, the simulations include the Fresnel reflections off the back surface and all multiple reflections. Further adjustments to the simulation would likely lead to even greater correlation with the measured data such as more accurate numbers for the indices of the oxide layers. However, it is clear that the inclusion of the oxide layers greatly increases agreement with the measured data with no need to account for non-ideal gap distance or rounding of metal corners on the SRR.

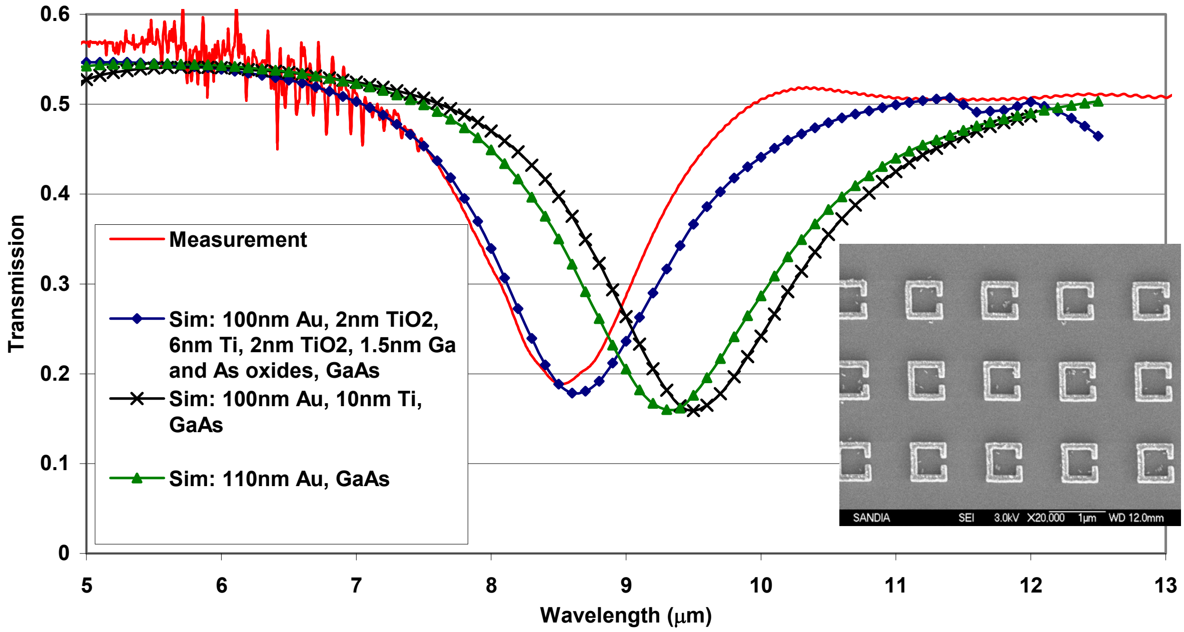

Fig. 2. Measured transmission and simulated transmission for Au on GaAs, Au + Ti adhesion layer on GaAs, and Au + Ti adhesion layer + oxides on GaAs.

4. SRRs on Silicon Substrate

With silicon we have the ability to more precisely control the oxide layer than with GaAs. Using a silicon wafer with a hydrogen-terminated surface we are able to measure a SRR with no oxide layer between the high-index substrate and the metal. We may then compare that to a similar structure with a native oxide layer on the silicon and a Ti oxide layer. Fabrication and measurement of SRRs on Si without the oxide layer are underway.

In Fig. 3 we see the effect of simulating the silicon structure with and without its native oxide. Including the oxide layer clearly results in a closer match to the measured data. As in the case of the GaAs device, the transmission curve is shofted to longer wavelength if the oxide layer is not included in the simulation.

A loss band related to the Si-O bond vibration occurs near 8µm, and the additional absoprtion can be seen in the FTIR measurement. This feature is reproduced accuractly in the simulation using the optical constants of the Si native oxide which were measured using an IR V.A.S.E. system (J.A. Woolam).

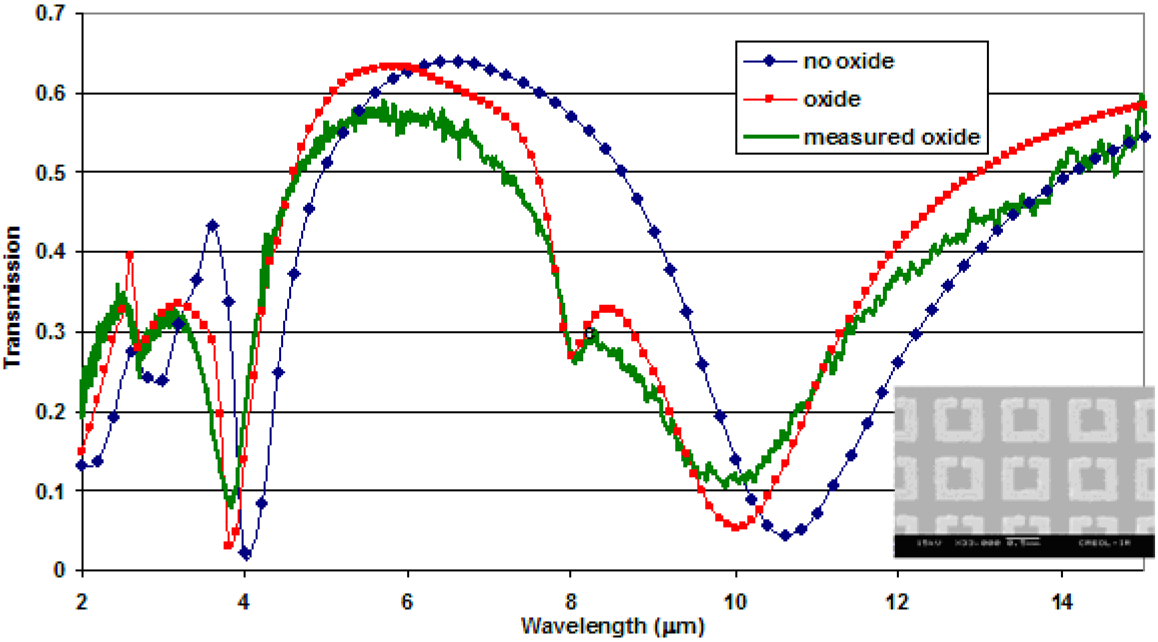

Fig. 3. Measurement and simulation of the SRR on silicon of Fig. 1.

5. Conclusion

We demonstrate that oxide layers with a thickness as small as 2nm (less than 1/1000 of the wavelength) can have a significant effect on the resonant frequency of split ring resonator metamaterials. Inclusion of these layers in the simulations greatly improves the agreement with the measured data.

Acknowledgment

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References

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