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Increasing the sensitivity of terahertz metamaterials for dielectric sensing by substrate etching

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***Abstract*—We investigate the effect of the effective substrate refractive index on the sensitivity of terahertz (THz) metamaterials for dielectric sensing by substrate etching. We found the effective refractive index near the metamaterials can be actively controlled by etching, allowing optimization of the sensitivity. Our experimental findings are in good agreement with finite element method (FEM) simulation results.**

I. INTRODUCTION

METAMATERIALS have been intensively investigated in the last decade owing to their unique properties such as negative refractive index and super-lensing, as well as their suitability for dielectric sensing [1]. Metamaterials typically comprise metal structures supporting various resonances such as inductive-capacitive (*LC*), dipole, and quadrupole resonances. The *LC* resonance is particularly interesting since it is highly sensitive to changes in the dielectric environment. The *LC* resonant frequency of free-standing split-ring resonators (SRR) can be expressed by the following equation: $f_0 = 1/2\pi\sqrt{LC}$, where L is the inductance of the ring and C is the capacitance of the gap. The resonance frequency can be altered if the effective refractive index near the gap changes. For example, the *LC* resonant frequency will shift if a dielectric analyte is placed in the gap area of resonator, since the capacitance of the gap will change. The shift in *LC* resonance induced can be expressed as $f = f_0(\varepsilon/\varepsilon_{\text{eff}})^{-\frac{1}{2}}$, where ε is the modified effective dielectric constant owing to the presence of the dielectric material in the gap area, and ε_{eff} is the effective dielectric constant in the gap area before introduction of the dielectric material [1]. We note the size of the resonant frequency shift can be increased by reducing ε_{eff}. Here, we develop a new way to produce a sensitivity enhancement of THz metamaterials by substrate etching [2].

II. RESULTS

Figure 1(a) shows a scanning electron microscopy (SEM) image of a fabricated resonator prepared with a 1.74-µm-deep trench etched into the *LC* gap. All metamaterials were patterned using direct-write laser lithography on a high-resistivity (>10,000 Ω·cm) undoped silicon substrate. Ti (10 nm) and Au (100 nm) metal layers were deposited by e-beam evaporation. A positive photoresist was spin-coated and patterned into an etch mask before trenches were formed within every *LC* gap using reactive ion etching. Cross-sectional SEM images of the etched metamaterials with two different etch depths (1.74 µm and 130 nm) are shown in Fig. 1(b) and (c) respectively.

The enhancement in device sensitivity for varying thicknesses of dielectric material deposited onto the THz SRRs was investigated both with and without the etched trenches. The resonant frequency of metamaterials as a function of dielectric thickness were compared in Fig. 1(d) for three conditions: (i) un-etched, (ii) with a 0.33 µm etch depth, and (iii) with a 3.4 µm etch depth. The resonant frequency shift increases until it saturates at a specific thickness since the electric field at the resonance is highly confined within the gap. The resonance shift also increases with trench depth owing to the decrease in the ε_{eff}. From Fig. 1(d), the sensitivities were extracted by dividing the initial slope of the resonant frequency shift–S1813 layer thickness curves in the linear region (thickness of S1813 layer < 1 µm) by the refractive index as shown in Fig. 1(e). The sensitivity of the metamaterial sensor increases from 4.3 × 10^{-2} GHz/nm (un-etched) to 11.6 × 10^{-2} GHz/nm (3.4-µm etch), which is an increase of ~2.7 times.

In FEM simulation results, the sensitivity increases ~ 2.9 times from 3.5 × 10^{-2} GHz/nm (un-etched) to 10.3 × 10^{-2} GHz/nm (3.4-µm etch). Our experimental findings are in good agreement with FEM simulation results.

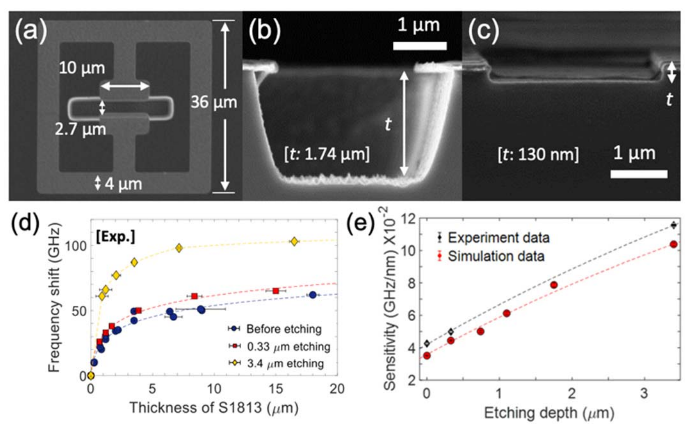

Fig. 1. (a) An SEM image of the metamaterial with a trench depth of 1.74 µm. Cross-section SEM images of the metamaterials with trench depths of (b) 1.74 µm and (c) 130 nm in the gap. (d) Resonant frequency shift as a function of S1813 thickness for various trench depths in the range of 0 – 3.4 µm (e) Sensitivities extracted from the initial slopes in (d) (black dots) and from simulation results (red dots) as a function of the trench depth for un-etched, 0.33 µm, and 3.4 µm.

III. SUMMARY

We demonstrated a sensitivity enhancement of a THz metamaterial dielectric sensor by the introduction of etched trenches, which reduces the local effective dielectric constant. Our approach overcomes the limitations of previously reported sensitivity enhancement methods based on the use of a lower-index or ultrathin substrate.

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