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Terahertz Field Induced Electromigration

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Abstract—**We report the first observation of THz-field-induced electromigration in sub-wavelength metallic gap structures after exposure to intense single-cycle, sub-picosecond electric field transients of amplitude up to 400 kV/cm.**

I. INTRODUCTION

WHEN a metal carries a sufficiently strong electric current, collisions transfer momentum from the conduction electrons to the atomic lattice. This momentum transfer, often referred to as an "electron wind," competes against the direct force of the applied electric field on the lattice atoms. The interplay of these two forces causes the shape of the metal to slowly deform, or migrate, due to the intense applied electric field [1]. This short description is the essence of electromigration. While this phenomenon has been studied extensively at lower frequencies due to its role in the failure of integrated circuits there are, to the best of our knowledge, no reports of electromigration at terahertz (THz) frequencies.

We have observed substantial THz induced damage, which we attribute to electromigration, in sub-wavelength metallic structures as shown in Figure 1. Our investigation indicates that the damage shown is metal deformation that forms a conducting bridge between the two structures.

II. SAMPLE FABRICATION

The samples are 200nm thick gold antennas patterned on a thick high-resistivity silicon (HR-Si) wafer using standard UV photolithography. There are two dipole antennas per unit cell. The two antennas are each 80.9 µm long and 5µm wide, and are aligned end to end with a small gap region between them. Samples with gaps of 1, 5, 7.5, and 10 µm are presented here, and the damage pattern shown in Figure 1 is for a 1 µm gap. The unit cell size is 141 µm by 282 µm. This antenna pattern is then arrayed in two dimensions over the HR-Si wafer and has a transmission resonance at 0.6 THz. At this frequency the incident electric field is strongly enhanced near the antenna tips, with an even larger enhancement in the gap region between the two antennas [2]. In Figure 1 (c), we overlay a computer simulation of the electric field pattern at the 0.6 THz resonance, clearly indicating that the observed damage closely follows the direction of the electric field.

III. RESULTS

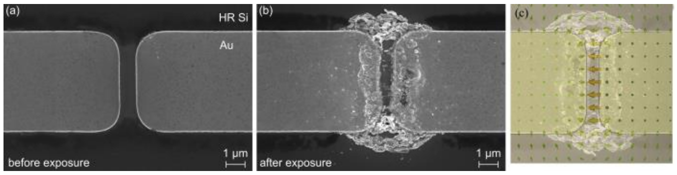

Fig. 1. Scanning electron microscope pictures of the THz induced damage. (a) and (b) show the gap between the antennas before and after THz exposure, respectively. (c) The simulated electrical field overlaid with the experimental damage.

The fabricated samples were exposed to incident THz electric fields of up to 400 kV/cm. Taking into account the simulated field enhancement factor of the antenna structure, the electric field in the center of the gap was estimated to > 2 MV/cm for all samples, with the smaller gap samples having even higher field strengths [2]. The samples were measured continuously using THz time domain spectroscopy for approximately one hour, and Figure 2 shows the transmission response at 0.333 and 0.608 THz as a function of exposure time. These figures are normalized to the transmission at time = 0, and show the relative decrease (increase) of the transmission at 0.333 THz (0.608 THz), respectively. This suggests that the antenna gap is shorting out and the structure is behaving as a single antenna of twice the length, instead of two coupled antennas. This behavior is consistent with computer simulations of a variable resistance in the gap region (not shown).

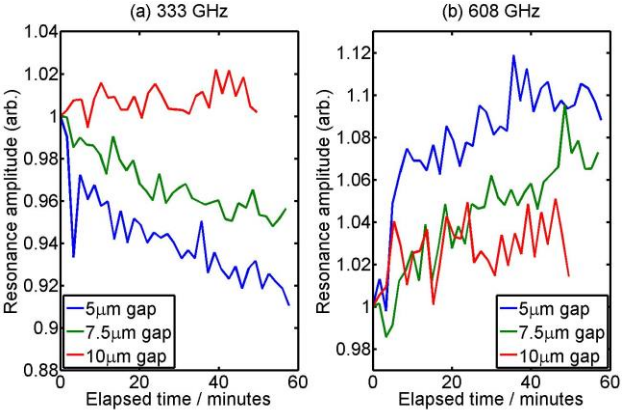

Fig. 2. The experimental change in transmission as a function of time suggests that a conduction path is being formed between the two antennas.

IV. CONCLUSION

In conclusion, we have made the first observation of THz field induced electromigration. We anticipate these results to have a significant impact on designing and interpreting THz studies combining strong electric fields with metallic structures. As switching times in modern nanotransistors approach the THz regime, our results could represent an important stepping stone towards a new method for testing both short- and long-term damage to ultrafast electronics due to the electric fields in the transistors during operation.

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