Terahertz Induced Electromigration

Andrew C. Strikwerda*, Maksim Zalkovskij, Krzysztof Iwaszczuk, and Peter Uhd Jepsen
DTU Fotonik – Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
astr@fotonik.dtu.dk

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.
OCIS codes: (300.6495) Spectroscopy, terahertz; (160.3918) Metamaterials; (240.0310) Thin films.

1. Introduction and background

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. 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, to the best of our knowledge, there are no reports in the literature on the observation 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.

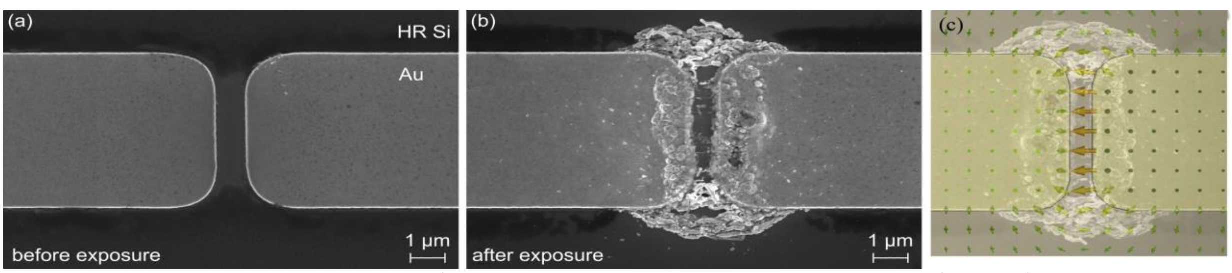

Figure 1 –Scanning electron microscope pictures of the THz induced damage. (a) and (b) show the sample before and after THz exposure, respectively. (c) shows a computer simulation of the electric field overlapped with the damage. In all cases, the pictures are close ups of the gap region between two dipole antennas.

2. 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 array is then arrayed in two dimensions over the HR-Si wafer and has a single 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 and migration of the gold closely follows the direction of the electric field.

3. Simulation and experimental results

To more accurately simulate the anticipated macroscopic response of electromigration, a lumped element resistor was added across the gap between the two antennas. As the resistance of the lumped element changes, mimicking the onset of a conduction path between the two antennas, the simulated transmission response of the structure fundamentally changes. If the resistance is large, the structure behaves as two coupled antennas. If the resistance decreases, the two dipole antennas will instead function as one longer antenna resonant at 0.33 THz. This simulated behavior is shown Figure 2, where the resistance of the lumped element across a 5 µm gap region is swept from 10 kΩ to 10 Ω.

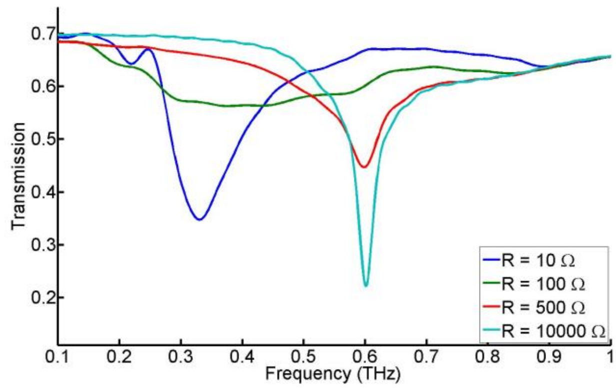

Figure 2 – The simulated change in transmission due to decreasing resistance between the two dipole antennas.

To verify this prediction, 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 3 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 t = 0, and show the relative decrease (increase) of the transmission at 0.333 THz (0.608 THz), respectively, consistent with the computer simulation. It is worth noting that the change in transmission occurs more rapidly with smaller gaps, ie. increasing electric field enhancement factor.

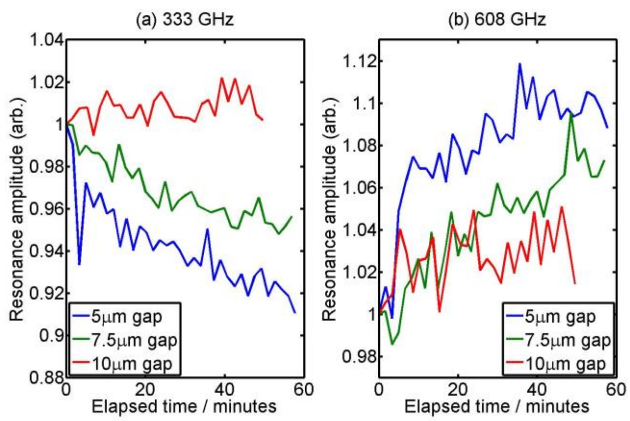

Figure 3 – The experimental change in transmission as a function of time. When compared with the simulated results from Figure 2, we can see that the gap between the two antennas is slowly being shorted.

4. Conclusion

Our experimental and numerical findings show that the high field THz transients are inducing electromigration, or electrically induced mass transport, in our antenna structures. In particular, our simulations and spectroscopic results indicate that the gap between the two dipoles is shorting out due to exposure to high field THz transients. This is consistent with the damage observed by electron microscopy, which appears to be a conducting bridge of gold across the gap region that closely matches the electric field lines.

In conclusion, we have made the first observation of THz-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.

6. References

[1] C. M. Tan and A. Roy, "Electromigration in ULSI interconnects," *Mater. Sci. Eng. R Reports*, vol. 58, no. 1–2, pp. 1–75, Oct. 2007.

[2] C. A. Werley, K. Fan, A. C. Strikwerda, S. M. Teo, X. Zhang, R. D. Averitt, and K. A. Nelson, "Time-resolved imaging of near-fields in THz antennas and direct quantitative measurement of field enhancements," *Opt. Express*, vol. 20, no. 8, p. 8551, Mar. 2012.