Electric and Magnetic Responses in Nonlinear Terahertz Metamaterials

Harold Y. Hwang[1,2,3], **Nathaniel C. Brandt**[1], **Kebin Fan**[2], **Xin Zhang**[2], **Richard D. Averitt**[3], **Keith A. Nelson**[1]
[1]*Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA 02139 USA*
[2]*Department of Mechanical Engineering, Boston University, Boston, MA 02215 USA*
[3]*Department of Physics, Boston University, Boston, MA 02215 USA*
hhwang82@mit.edu

Abstract: We report THz electric and magnetic field-induced nonlinear responses in metamaterial structures. We demonstrate air breakdown in SiN_x metamaterials with THz electric fields, and highly nonlinear responses in 3D silicon metamaterials with THz magnetic fields.

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The development of free space THz sources with microjoule pulse energies has enabled investigations of carrier dynamics in a variety of semiconducting materials [1-2]. Enhancement of THz electric fields with metamaterial split ring resonator (SRR) structures has made field strengths in excess of 1 MV/cm accessible. Highly nonlinear carrier transport processes have been observed in GaAs using metamaterial-enhanced nonlinear THz spectroscopic techniques [3]. Though THz-induced damage has been observed in both GaAs [3], and vanadium dioxide [4], controlled investigation of breakdown mechanisms and thresholds with ultrafast THz pulses have yet to be demonstrated. Furthermore, the large peak magnetic field (a 1 MV/cm electric field corresponds to a 0.33 T magnetic field) of intense THz radiation has yet to be utilized to drive nonlinear processes in matter. Here, we present recent results revealing a THz magnetic field induced *electronic* nonlinearity in high-resistivity (hi-res) silicon, and THz electric field induced air breakdown in silicon nitride (SiN_x) air-gap metamaterials.

Single cycle THz pulses with energies of 6 μJ were generated using the tilted pulse front technique, yielding peak field strengths of several hundred kV/cm. Both nonlinear THz transmission and THz-pump/THz-probe spectroscopy were used to observe the conductivity response locally in the SRR capacitive gaps.

For hi-res silicon experiments, 2D planar metamaterials were used to study the electric-field induced response, and 3D out-of-plane metamaterials were used to study the magnetic-field induced response. At 15 kV/cm incident THz field, the 2D SRR absorption exhibits a strong and narrow LC resonance at 0.86 THz (fig. 1a). As field strengths increase to 100 kV/cm, the peak transmission increases smoothly, with the resonance slightly redshifting and broadening. Increasing field strengths beyond 100 kV/cm shows dramatic broadening of the absorption feature along with a blueshift in the absorption maximum to 0.87 THz. These phenomena indicate a considerable increase in

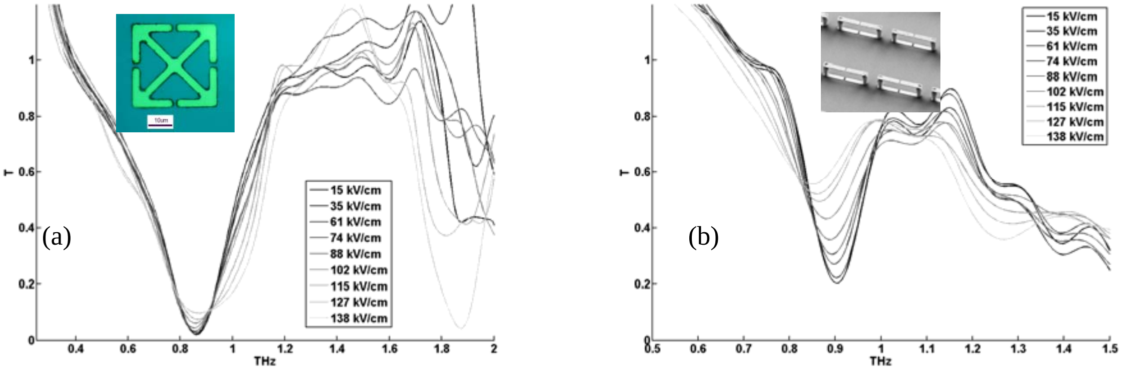

Fig. 1 (a) Transmission through 2-D SRR array on Si at various THz field strengths; inset shows 2-D SRR structure. (b) Transmission through 3-D SRR array at various THz field strengths; inset shows 3-D SRR structure.

the conductivity of the Si in the SRR capacitive gaps due to competing responses as carriers—generated by high-field nonlinear carrier transport processes—are accelerated by the gap-enhanced THz field. The 3D MM sample exhibits a much stronger monotonic redshift with increasing field along with a gradual peak broadening, and a stronger relative change in the resonant response of the metamaterial (fig. 1b). Simulations indicate that this is consistent with an increase in conductivity in the gap in contact with the Si substrate only. By geometry, the 3D silicon metamaterial can only have a response that is related to the THz magnetic field. The THz electric field cannot couple to the LC resonance of the 3D SRRs, and the dipole resonance is outside the bandwidth of the incident THz pulse. Therefore the magnetic field of the THz field must drive a strong current in the SRRs, coupling to the LC resonance which subsequently causes large localization of the charge density at each end a capacitive gap contacting the silicon. This drives nonlinear carrier transport processes in silicon which causes the subsequent increase of the conductivity in the capacitive gaps of the SRRs. Our results demonstrate an exciting route to nonlinear effective magnetic susceptibilities and enhanced nonlinear metamaterial responses via a 3D MM geometry.

For SiN_x air-gap metamaterial experiments, planar metamaterial SRRs were patterned on 400 nm thick SiN_x, where the SiN_x was etched to remove all the material in the vicinity of the capacitive gaps (fig. 2a).

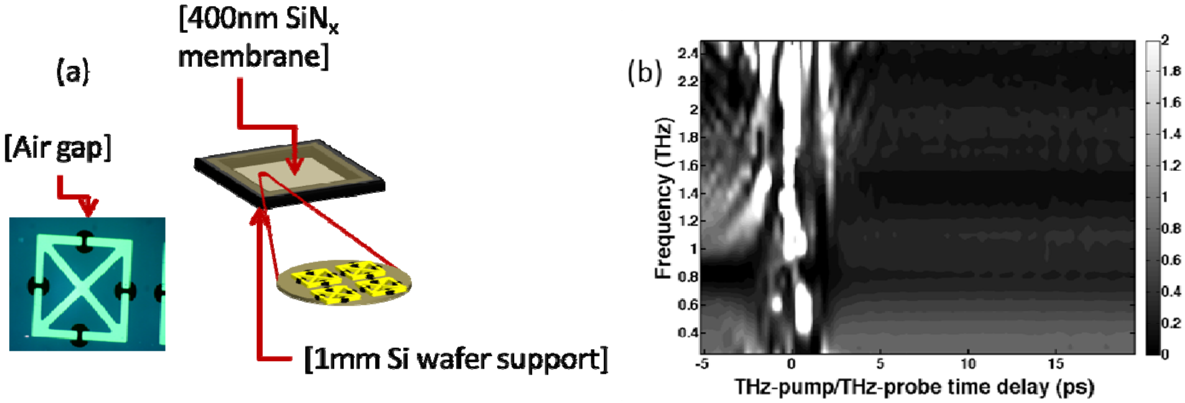

Fig. 2: (a) SiN_x air-gap metamaterials. The regions around each capacitive gap is etched away, leaving only free-space. (b) THz-pump/THz-probe measurement of the air-gap metamaterial response. The frequency-dependent transmission is plotted versus pump/probe delay time. There is a strong resonance near 0.8 THz before the arrival of the pump. After the pump arrives, there is a clear change in the 0.8 THz resonance to higher transmission indicating an increase in the conductivity of the air in the capacitive gaps.

THz-pump/THz-probe measurements indicate a conductivity increase in the capacitive gaps after the arrival of the THz-pump pulse since the 0.8 THz resonance of the SRRs begins to disappear (fig 2b). Since only air is in the capacitive gaps of the SRRs, we attribute the increase in the transmission at 0.8 THz to ionization of air.

Our recent results show novel capabilities of the metamaterial-enhanced nonlinear THz spectroscopy platform, which may lead to new advances in studying ultrafast magnetic field induced processes, as well as highly nonpertubative processes at THz frequencies in molecular systems.

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