THz materials discovery and integration: the search for novel functionality

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Abstract—**The functionality of terahertz metamaterials can be dramatically increased through judicious materials integration. In addition to semiconductors, materials ranging from graphene to superconductors can enhance or enable new functionality. Following a brief review, we present recent results creating nonlinear metamaterials using InAs and $YBa_2Cu_3O_7$, and discuss the broad range of possibilities to explore using transition metal oxides in the design of metamaterials.**

I. INTRODUCTION

THE field of metamaterials is approximately 15 years old, and the sub-area of terahertz metamaterials is more than a decade old. There have been numerous advances during this time with materials integration to control the electromagnetic response of metamaterial resonators being particularly fruitful. Considerable focus and effort has been directed towards integrating semiconductors into the active regions of split ring resonators (SRR) [1]. This enabled optical and electrical control allowing for the demonstration of functional modulators, detectors, waveplates, and more recently, perfect absorbers.

The area of active, reconfigurable, and nonlinear terahertz (THz) metamaterials (MM) has continued to advance with important demonstrations utilizing materials beyond conventional semiconductors. For example, graphene has been utilized to create tunable metamaterial and plasmonic devices at THz frequencies [2], [3]. One can envision that other 2D layered materials such as transition metal dichalcogenides (e.g. MoS_2, WSe_2) will also be of interest [4]. Another interesting advance has been the incorporation of liquid crystals with SRRs to create a MM-based absorber for spatial light modulation [5].

Transition metal oxides (TMOs) are another class of materials of interest for potential terahertz metamaterials integration. This includes high temperature superconductors and materials that exhibit insulator-to-metal transitions. The impressive advances in the epitaxial growth of TMOs has resulted in ultrathin films with properties comparable to single crystals which facilitates incorporation with MM and related devices. Several important demonstrations incorporating TMOs into MM have been demonstrated.

For example, vanadium dioxide (VO_2) exhibits an insulator to metal transition (IMT) at 340K with a change in the conductivity of several orders of magnitude. Importantly, the IMT in VO_2 is first order and thus exhibits hysteresis in the conductivity. This has been exploited to create memory metamaterials [6]. Further, VO_2 integrated with SRRs exhibits a nonlinear response in high-field THz studies [7].

High temperature superconductors have also been utilized in creating novel THz MM. SRRs have been directly fabricated from superconductors. For example, SRRs have been fabricated from $YBa_2Cu_3O_7$, a canonical high-T_c superconductor with a transition temperature of ~90K [8]. As a function of temperature, efficient resonance switching and tuning was demonstrated and, further, it has been shown that these materials exhibit a non-linear response upon high-field THz irradiation [9]. We mention that conventional BCS superconductors such as Nb and NbN have also been used to create novel THz metamaterials [10]. This includes a recent demonstration using Nb thin films as high Q resonators [11] (superconductors also play an important role in creating novel microwave metamaterials [12]).

These examples highlight that novel materials can favorably augment the response of MM. This can be accomplished through integration with metallic resonators or conventional metals such as gold can be eliminated entirely as in the case of high-T_c superconductors. In the following we present of examples of our recent work that fit this theme. This includes InAs plasmonic resonators, and YBCO perfect absorbers.

II. RESULTS

As a first example, we have created plasmonic semiconductor metamaterials that are resonant at THz frequencies. Our plasmonic devices are fabricated from n-doped InAs (n-InAs) thin films patterned into disk arrays. High-field terahertz transmission measurements reveal that the

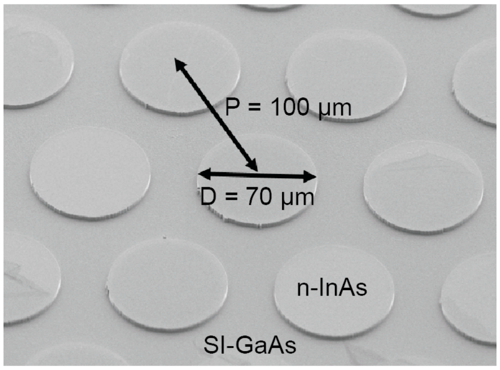

Fig. 1. InAs disk array on semi-insulating GaAs. (b) SEM image of the fabricated PSCMM: InAs film thickness: 2 µm, SI-GaAs substrate thickness = 500 µm, disk diameter (D) = 70 µm, periodicity (P) = 100 µm.

disk plasmon resonance is nonlinear arising from field induced intervalley scattering to a low-mobility side valley. A disk array composed of 70 µm diameter n-InAs disks with 100 µm hexagonal lattice periodicity was fabricated as shown in Figure 1.

InAs was chosen since carriers in the conduction band have a high mobility ($\sim 20\times10^3$ cm^2/Vs). This makes n-InAs an attractive plasmonic material for THz frequencies since the plasmon resonance width is inversely proportional to the mobility. The plasmon resonance will exhibit a carrier density dependence and our samples were doped to 10^{17} cm^{-3} to, as shown below, obtain a strong plasmonic response at ~0.8THz.

High field THz time domain spectroscopy (TDS) was employed to characterize the samples. Figure 2 shows the plasmon resonance as a function of frequency at various incident field strengths with an estimated maximum around E_0 = 300 kV/cm. At the lowest field (0.1E_0 - black curve), a well-defined resonant transmission dip is evident at 0.77 THz. With increasing field strength there is a dramatic increase in the transmission – that is, the plasmon resonance is strongly damped. When the THz pulse reaches its maximum peak strength (E_0 – purple curve), the increase in transmission is approximately 40% in comparison to the low field measurements.

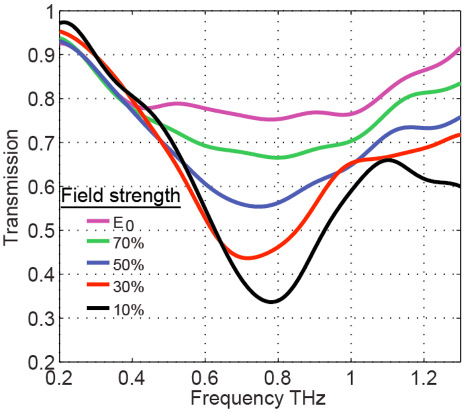

Fig. 2. Measured transmission amplitude of InAs array shown in Figure 1 for various THz field strengths.

The band structure of InAs plays an important role in the plasmonic response. The doped carriers reside in the gamma valley with a small effective mass (and resultant high mobility). The oscillator strength of the plasmon resonance is modified through intervalley scattering. Specifically efficient intervalley scattering (Γ→ L) results in a damping of the plasmon resonance because of the considerably larger effective mass (and reduced mobility) of carriers in the L valley.

As a second example, we present a superconducting metamaterial saturable absorber at terahertz frequencies. The absorber consists of an array of split ring resonators (SRRs) etched from a 100nm $YBaCu_3O_7$ (YBCO) film. A polyimide spacer layer and gold ground plane are deposited above the SRRs to create a reflecting perfect absorber geometry. The top portion of Fig. 3 depicts the absorber structure.

The MM absorption has a strong nonlinear dependence on incident field strength and functions as a saturable absorber over a broad range in temperature. The bottom of Figure 3 shows the MM absorption spectra for varying incident field strength at 10K. Increasing the incident electric field from 40kV/cm to 200kV/cm causes the MM absorption peak to saturate from 0.70 to 0.40, corresponding to an electric field induced modulation of 42%.

III. SUMMARY

In summary, advances in MM technology and devices can benefit from broad consideration of functional properties of numerous classes of materials. Material properties that appear exotic today may one day find commonplace application in advancing terahertz technology.

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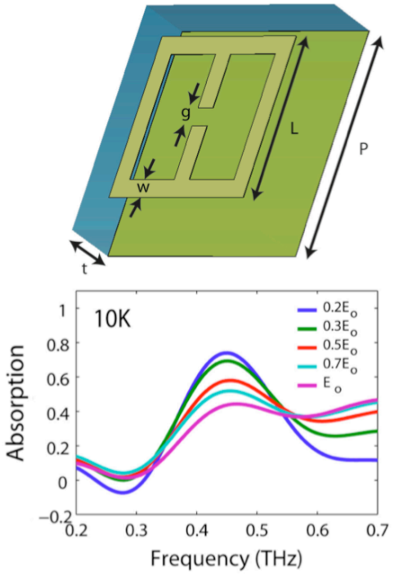

Fig. 3. Top image show YBCO perfect absorber SRR with relevant dimensions. The SRR side length is L=40µm, unit cell periodicity, P=56µm, linewidth, w=5µm, and the capacitive gap width, g=3µm. The polyimide spacer layer t = 3µm, between the YBCO and Au ground plane. Bottom: absorption spectrum at various incident fields (E_o = 200kV/cm).

REFERENCES

[1] K. Fan and W. J. Padilla, "Dynamic electromagnetic metamaterials," *Mater. Today*, vol. 18, no. 1, pp. 39–50, Jan. 2015.

[2] L. Ju, B. Geng, J. Horng, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl, Y. R. Shen, and F. Wang, "Graphene plasmonics for tunable terahertz metamaterials.," *Nat. Nanotechnol.*, vol. 6, no. 10, pp. 630–4, Oct. 2011.

[3] S. H. Lee, M. Choi, T.-T. Kim, S. Lee, M. Liu, X. Yin, H. K. Choi, S. S. Lee, C.-G. Choi, S.-Y. Choi, X. Zhang, and B. Min, "Switching terahertz waves with gate-controlled active graphene metamaterials.," *Nat. Mater.*, vol. 11, no. 11, pp. 936–41, Nov. 2012.

[4] C. J. Docherty, P. Parkinson, H. J. Joyce, M.-H. Chiu, C.-H. Chen, M.-Y. Lee, L.-J. Li, L. M. Herz, and M. B. Johnston, “Ultrafast Transient Terahertz Conductivity of Monolayer MoS 2 and WSe 2 Grown by Chemical Vapor Deposition,” *ACS Nano*, vol. 8, no. 11, pp. 11147–11153, Nov. 2014.

[5] S. Savo, D. Shrekenhamer, and W. J. Padilla, “Liquid Crystal Metamaterial Absorber Spatial Light Modulator for THz Applications,” *Adv. Opt. Mater.*, vol. 2, no. 3, pp. 275–279, Mar. 2014.

[6] T. Driscoll, H.-T. Kim, B.-G. Chae, B.-J. Kim, Y. W. Lee, N. M. Jokerst, S. Palit, D. R. Smith, M. Di Ventra, and D. N. Basov, “Memory Metamaterials,” vol. 325, no. 1518, 2009.

[7] M. Liu, H. Y. Hwang, H. Tao, A. C. Strikwerda, K. Fan, G. R. Keiser, A. J. Sternbach, K. G. West, S. Kittiwatanakul, J. Lu, S. A. Wolf, F. G. Omenetto, X. Zhang, K. A. Nelson, and R. D. Averitt, “Terahertz-field-induced insulator-to-metal transition in vanadium dioxide metamaterial.,” *Nature*, vol. 487, no. 7407, pp. 345–8, Jul. 2012.

[8] H.-T. Chen, H. Yang, R. Singh, J. F. O’Hara, A. K. Azad, S. A. Trugman, Q. X. Jia, and A. J. Taylor, “Tuning the Resonance in High-Temperature Superconducting Terahertz Metamaterials,” *Phys. Rev. Lett.*, vol. 105, no. 24, p. 247402, Dec. 2010.

[9] N. K. Grady, B. G. Perkins, H. Y. Hwang, N. C. Brandt, D. Torchinsky, R. Singh, L. Yan, D. Trugman, S. A. Trugman, Q. X. Jia, A. J. Taylor, K. A. Nelson, and H.-T. Chen, “Nonlinear high-temperature superconducting terahertz metamaterials,” *New J. Phys.*, vol. 15, no. 10, p. 105016, Oct. 2013.

[10] C. Zhang, B. Jin, J. Han, I. Kawayama, H. Murakami, J. Wu, L. Kang, J. Chen, P. Wu, and M. Tonouchi, “Terahertz nonlinear superconducting metamaterials,” *Appl. Phys. Lett.*, vol. 102, no. 8, p. 081121, 2013.

[11] G. Scalari, C. Maissen, S. Cibella, R. Leoni, and J. Faist, “High quality factor, fully switchable terahertz superconducting metasurface,” *Appl. Phys. Lett.*, vol. 105, no. 26, p. 261104, Dec. 2014.

[12] P. Jung, A. V Ustinov, and S. M. Anlage, “Progress in superconducting metamaterials,” *Supercond. Sci. Technol.*, vol. 27, no. 7, p. 073001, Jul. 2014.