Advanced Photoconductive Terahertz Optoelectronics Based on Nano-Antennas and Nano-Plasmonic Light Concentrators

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(Invited Paper)

***Abstract*—High power sources and high sensitivity detectors are highly in demand for terahertz imaging and sensing systems. Use of nano-antennas and nano-plasmonic light concentrators in photoconductive terahertz sources and detectors has proven to offer significantly higher terahertz radiation powers and detection sensitivities by enhancing photoconductor quantum efficiency while maintaining its ultrafast operation. This is because of the unique capability of nano-antennas and nano-plasmonic structures in manipulating the concentration of photo-generated carriers within the device active area, allowing a larger number of photocarriers to efficiently contribute to terahertz radiation and detection. An overview of some of the recent advancements in terahertz optoelectronic devices through use of various types of nano-antennas and nano-plasmonic light concentrators is presented in this article.**

***Index Terms*—Nano-antennas, nanostructures, photoconductivity, plasmonics, terahertz detector, terahertz source.**

I. Introduction

THERE is a growing interest in developing high power terahertz sources and high sensitivity terahertz detectors for advanced imaging and sensing application [1]–[14]. Among various techniques for terahertz generation and detection, photoconduction has been one of the most promising and commonly used techniques [15]–[34]. An optical beam from a femtosecond mode-locked laser or two heterodyning optical beams with a terahertz frequency difference pump an ultrafast photoconductor connected to a terahertz antenna to generate/detect pulsed or continuous-wave terahertz radiation, respectively. Availability of high power, wavelength tunable, and compact optical sources with pulsed and continuous-wave operation has been a major driving force for use of photoconductive terahertz sources and detectors. However, the main obstacle of these devices that prevents high power terahertz generation and high sensitivity terahertz detection has been the inherent tradeoff between high quantum efficiency and ultrafast operation in conventional photoconductors. By looking closely at the operation of photoconductive terahertz sources and detectors, one can see that this inherent tradeoff is due to the limited carrier transport velocities in semiconductor substrates, which is bound by carrier scattering inside the semiconductor lattice. For efficient generation/detection of terahertz radiation in a photoconductive device, the transport time of the photo-generated carriers to the device contact electrodes should be a fraction of the terahertz oscillation cycle [35], [36]. Considering carrier drift velocity values in photo-absorbing semiconductor substrates, carrier transport path lengths of less than $\sim$100 nm are required for this purpose. Since focusing an optical beam into such sub-wavelength dimensions is diffraction limited, efficiency of conventional photoconductive terahertz sources and detectors is limited by relatively long transport path lengths of the photo-generated carriers within the device active area.

To address this limitation, several photoconductive terahertz sources and detectors based on optical nano-antennas and nano-plasmonic light concentrators have been demonstrated in recent years. By concentrating the optical pump beam in close proximity to the device contact electrodes and beyond the diffraction limit, a large portion of the photo-generated carriers is generated within nanoscale distances from the device contact electrodes and, thus, efficiently contributes to terahertz generation and detection. In this paper, we present an overview of some of the recent advancements in photoconductive terahertz sources and detectors based on optical nano-antennas and nano-plasmonic light concentrators, enabling significant enhancement in output power and detection sensitivity of photoconductive terahertz sources and detectors, respectively.

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II. Photoconductive Terahertz Sources and Detectors Based on Optical Nano-Antennas and Nano-Plasmonic Light Concentrators

A. Photoconductive Sources Based on Optical Nano-Antennas

The impact of incorporating optical nano-antennas inside the active area of photoconductive terahertz sources has been

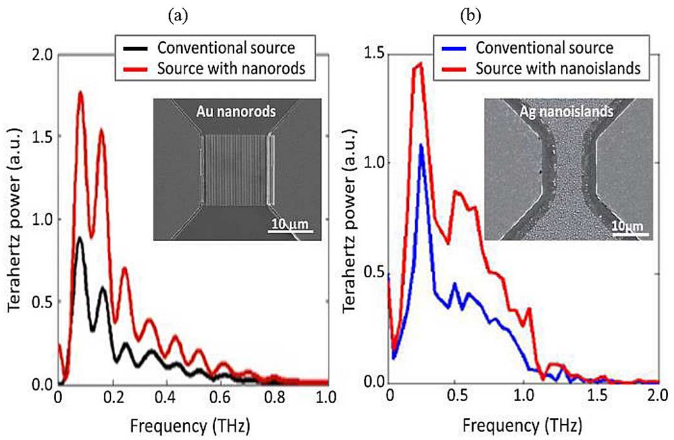

Fig. 1. Terahertz radiation enhancement by incorporating Au nanorod [37] and Ag nanoisland arrays [38] in the active area of a photoconductive source is illustrated in (a) and (b), respectively. Insets show the scanning electron microscope images of the fabricated devices.

explored in a recent study. For this purpose, an array of optical nano-antennas in the form of Au nanorod arrays [Fig. 1(a)] and Ag nano-island arrays [Fig. 1(b)] has been fabricated between the anode and cathode contact electrodes of photoconductive terahertz sources integrated with bow-tie antennas [37], [38]. The use of optical nano-antennas results in a tight confinement of the optical pump and, thus, high concentration of the photo-generated carriers near the contact electrodes at the plasmon resonance of the utilized nano-antennas. As a result, up to three times terahertz radiation enhancement levels have been achieved in pulsed operation.

B. Photoconductive Sources Based on Plasmonic Contact Electrode Gratings

The impact of nano-plasmonic contact electrodes on the performance of photoconductive terahertz sources has been also investigated in a recent study. For this purpose, the performance of a plasmonic photoconductive source with plasmonic contact electrode gratings [39], [40] has been analyzed together with a comparable conventional photoconductive source without plasmonic contact electrodes [see Fig. 2(a)] [36]. Bow-tie antennas with identical radiation properties have been used in this study and the photoconductive sources have been designed to induce the same parasitic loading to their respective terahertz antennas. Conventional and plasmonic sources have been fabricated side-by-side on the same low temperature grown (LT) GaAs substrate and characterized under the same operation conditions [41]. The radiated terahertz power from both sources pumped by a Ti:sapphire laser ($\lambda = 800$ nm) has been measured under various optical pump powers and bias voltages, indicating up to 50 times higher power levels radiated from the plasmonic source [Fig. 2(b)] [36]. This significant radiation enhancement is due to the use of plasmonic contact electrode gratings, which enhances the concentration of the photo-generated carrier in close proximity to the plasmonic contact electrode gratings. By reducing the average transport path length of the photo-generated carriers to the plasmonic contact electrodes, a larger portion of the photo-generated carriers is drifted to the terahertz antenna

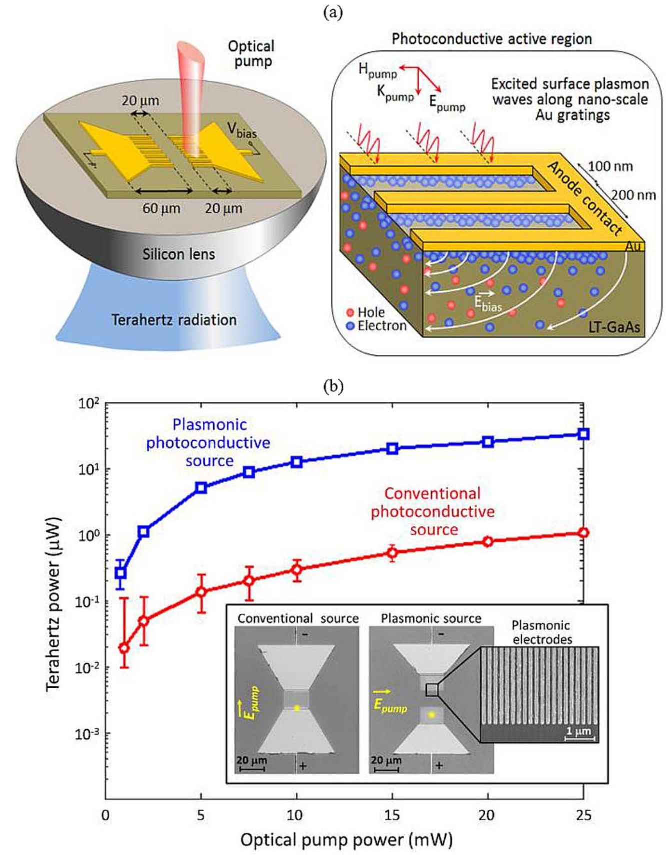

Fig. 2. (a) Schematic of a plasmonic photoconductive terahertz source with plasmonic contact electrode gratings. (b) Radiated power from the plasmonic photoconductive source and a comparable conventional photoconductive source under the same operation conditions [36].

within a sub-picosecond time-scale and, thus, higher terahertz power levels are achieved.

It should be noted that the photocarrier concentration enhancement in close proximity to the plasmonic contact electrode gratings is the result of two processes. The first process is excitation of surface waves on top of the plasmonic contact electrode gratings, which allows efficient transmission of the incident optical pump through the subwavelength gaps between the metallic electrodes into the photo-absorbing substrate. This is achieved by an appropriate choice of grating geometry to couple the incident optical wave to the guided modes supported by the metallic gratings through the excited surface waves [42]. The second process is tight confinement of the excited surface waves at the metal-semiconductor interface, the so called surface plasmon field enhancement, which is directly affected by the complex permittivity of the utilized metal at the optical pump wavelength.

The impact of plasmonic contact electrode gratings on enhancing the output power of photoconductive terahertz sources is universal and can be employed in various types of photoconductive terahertz source architectures with a variety of radiating antennas and bias feeds in both pulsed and continuous-wave operation [43]. As an example, the impact of incorporating plasmonic contact electrode gratings in a 3×3 array of

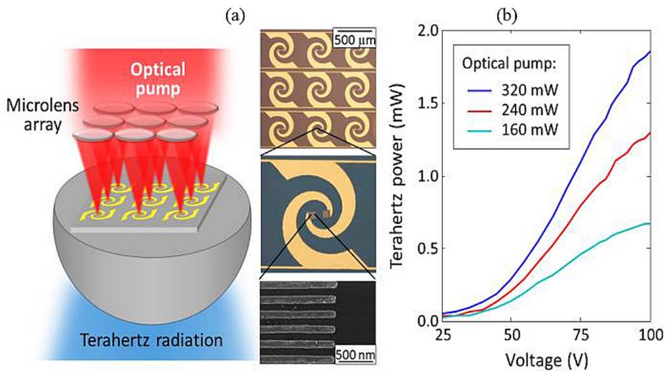

Fig. 3. (a) Schematic of a 3×3 plasmonic photoconductive source array with logarithmic spiral terahertz antennas. (b) Radiated terahertz power from the plasmonic photoconductive source array as a function of the bias voltage and pump power, when pumped by a Ti:sapphire laser (λ = 800 nm) [44].

photoconductive terahertz sources with logarithmic spiral antennas fabricated on a LT-GaAs substrate has been explored [Fig. 3(a)]. Terahertz radiation power levels as high as 2 mW have been achieved in pulsed operation. Such high radiation power levels have been possible not only by the high photoconductor quantum efficiencies offered by the plasmonic contact electrode gratings but also by the use of broadband logarithmic spiral antennas and by mitigating the carrier screening effect at high optical pump powers [Fig. 3(b)] [44].

C. Photoconductive Detectors Based on Plasmonic Contact Electrode Gratings

Following the study on photoconductive sources integrated with plasmonic contact electrodes, the impact of plasmonic contact electrode gratings on the performance of photoconductive detectors has been investigated. For this purpose, a conventional photoconductive detector without plasmonic contact electrodes and a plasmonic photoconductive detector with plasmonic contact electrode gratings are fabricated on the same LT-GaAs substrate and characterized under the same operation conditions. Bow-tie antennas with identical radiation properties have been used in this study [see Fig. 4(a)] and the performance of the fabricated photoconductive detectors has been investigated in a time-domain terahertz spectroscopy setup [36], [45]. Experimental results indicate 30 times higher responsivity levels offered by the plasmonic photoconductive detector compared to the conventional design [see Fig. 4(b) and (c)] [36], [45]. The experimental results also indicate the same output noise levels from the plasmonic and conventional photoconductive detectors, dominated by the Johnson–Nyquist noise [46]. Therefore, a 30-fold enhancement in terahertz detection sensitivity is offered by the plasmonic photoconductive detector [36], [45].

Similar terahertz detection sensitivity enhancement levels [Fig. 5(a)] have been also demonstrated by incorporating nano-interlaced contact electrodes in a photoconductive terahertz detector with a dipole terahertz antenna fabricated on a semi-insulating (SI) GaAs substrate [Fig. 5(b)] [47]. For this purpose, the plasmonic resonances of the interlaced structure have been used to efficiently couple the optical pump pulse into the narrow gaps between the contact electrodes. These gaps sweep out the generated photocarriers in a sub-picosecond

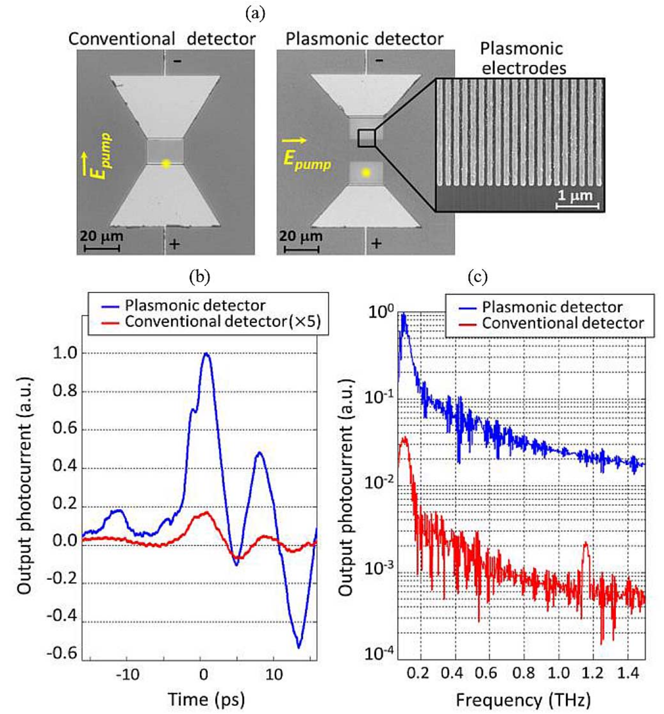

Fig. 4. (a) Scanning electron microscope images of the photoconductive detectors fabricated for investigating the impact of plasmonic contact electrode gratings on terahertz detection sensitivity. Measured output current of the photoconductive detectors in the (b) time domain and (c) frequency domain [36], [45].

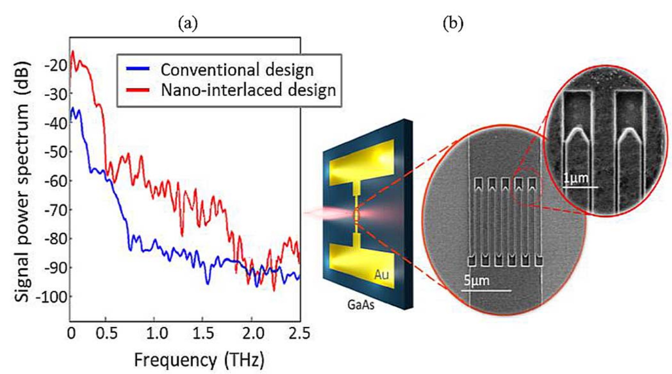

Fig. 5. (a) Terahertz detection sensitivity enhancement by use of nano-interlaced electrodes. (b) Schematic and scanning electron microscope images of the photoconductive detector with nano-interlaced electrodes [47].

time range allowing comparable bandwidths with a LT-GaAs device.

D. Large Area Photoconductive Sources Based on Plasmonic Contact Electrode Gratings

Another promising photoconductive terahertz source architecture that has been utilized to explore the impact of nanoplasmonic contact electrode gratings is large area photoconductive source architecture [48], [49]. Large area photoconductive sources can offer high power terahertz radiation because of their capacity to handle relatively high optical powers without suffering from the carrier screening effect and thermal breakdown. Additionally, they can offer broadband terahertz radiation due to the fact that the terahertz radiation is generated by time-

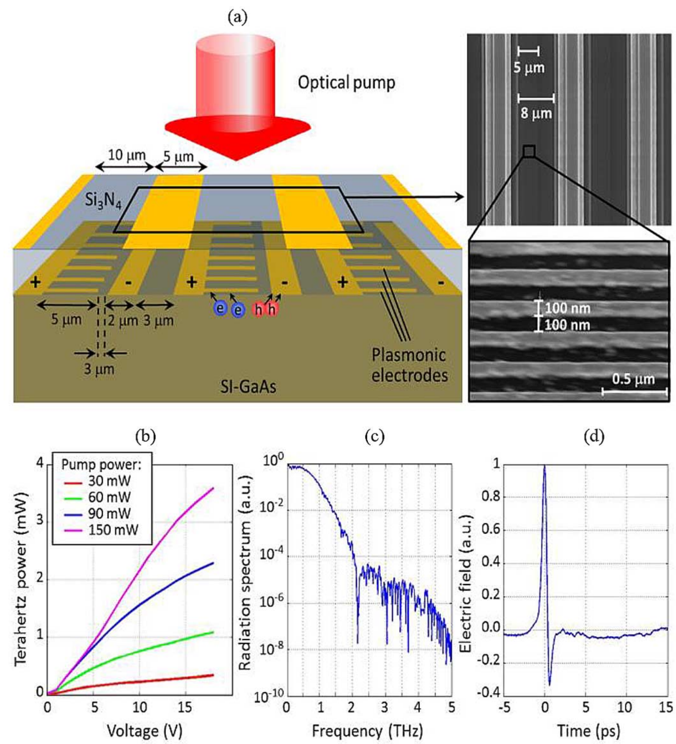

Fig. 6. (a) Schematic and scanning electron microscope images of a large area plasmonic photoconductive source fabricated on a SI-GaAs substrate. Radiated terahertz power from the large area plasmonic photoconductive source, the frequency-domain radiated power, and the time-domain radiated field are shown in (b), (c), and (d), respectively [48], [49].

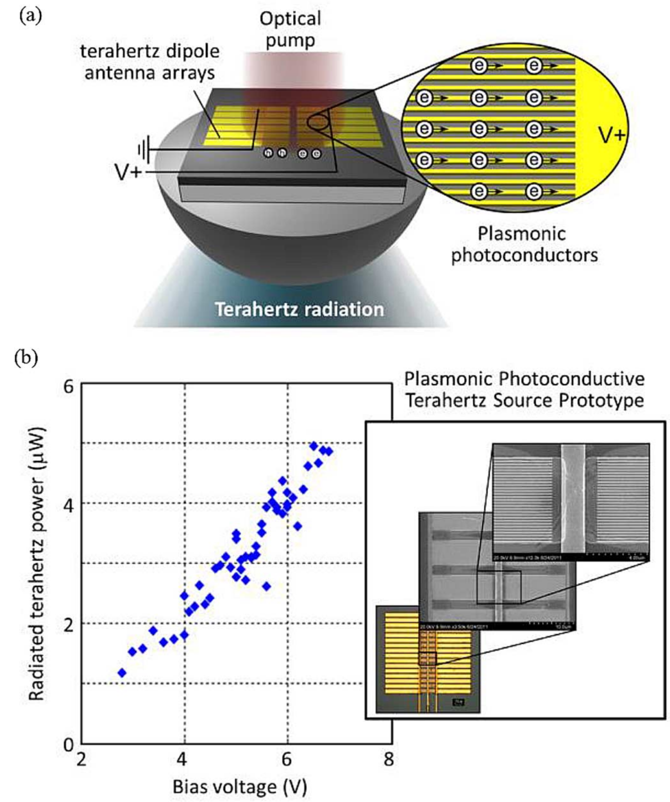

Fig. 7. (a) Schematic of a plasmonic photoconductive source with dipole terahertz antenna arrays on an epitaxially grown InGaAs substrate. (b) Measured terahertz power from the plasmonic photoconductive source with dipole terahertz antenna arrays as a function of the bias voltage under an optical pump power of 85 mW from a Ti:sapphire laser ($\lambda = 925$ nm) [35].

varying dipole moments induced within the device active area with dipole lengths much smaller than terahertz wavelengths. In a recent study, an array of plasmonic contact electrode gratings has been incorporated in the active area of a large area photoconductive source [Fig. 6(a)] and two orders of magnitude higher optical-to-terahertz conversion efficiencies has been achieved compared to previously demonstrated non-plasmonic large area photoconductive sources [23]. As such, pulsed terahertz radiation powers as high as 3.6 mW have been demonstrated at 150 mW optical pump power [Fig. 6(b)] over 0.1–5 THz frequency range [Fig. 6(c)] with a terahertz radiation pulse width of 0.5 ps FWHM [Fig. 6(d)] [48], [49].

Another advantage of using nano-plasmonic contact electrodes in photoconductive terahertz sources is that it eliminates the need for short-carrier lifetime semiconductors. This design flexibility is due to the fact that the ultrafast operation of plasmonic photoconductors is offered by photocarrier spatial manipulation in the device active area, rather than photocarrier recombination out of the device active area [35]. It should be noted that all of the utilized techniques for developing short-carrier lifetime semiconductors incorporate a high density of trap sites within the semiconductor lattice and therefore degrade carrier mobility and photoconductor quantum efficiency significantly. The high density of the trap sites in short-carrier lifetime semiconductors also degrades semiconductor's thermal conductivity, which leads to a premature thermal breakdown of photoconductors at high optical pump power levels. Therefore, plasmonic contact electrodes enable a new generation of high-performance photoconductive terahertz devices based on long-carrier lifetime semiconductors. As an example, a plasmonic photoconductive terahertz source with dipole terahertz antenna arrays has been implemented on an epitaxially grown InGaAs substrate [Fig. 7(a)] and its terahertz radiation in response to a Ti:sapphire laser ($\lambda = 925$ nm) has been characterized [35]. The results indicate significantly higher radiated power levels compared to previously demonstrated photoconductive sources with planar dipole antennas on short-carrier lifetime InGaAs substrates [Fig. 7(b)].

E. Photoconductive Mixers Based on Plasmonic Contact Electrode Gratings

The impact of nano-plasmonic contact electrodes on the performance of photoconductive terahertz sources has been also explored in continuous-wave operation [50], [51]. For this purpose, a photomixer with plasmonic contact electrode gratings and a logarithmic spiral antenna has been fabricated on an ErAs:InGaAs substrate [Fig. 8(a) and pumped with two wavelength-tunable continuous-wave optical sources ($\lambda \sim 1550$ nm) with a controllable frequency difference in the 0.25–2.5 THz range. In order to mitigate thermal breakdown at high optical pump powers, the optical pump has been modulated with a duty cycle of less than 10%. In the meantime, the modulation frequency of the optical pump has been chosen to limit the linewidth broadening of the radiated terahertz wave to less than 50 MHz. At an average optical pump power of 150 mW,

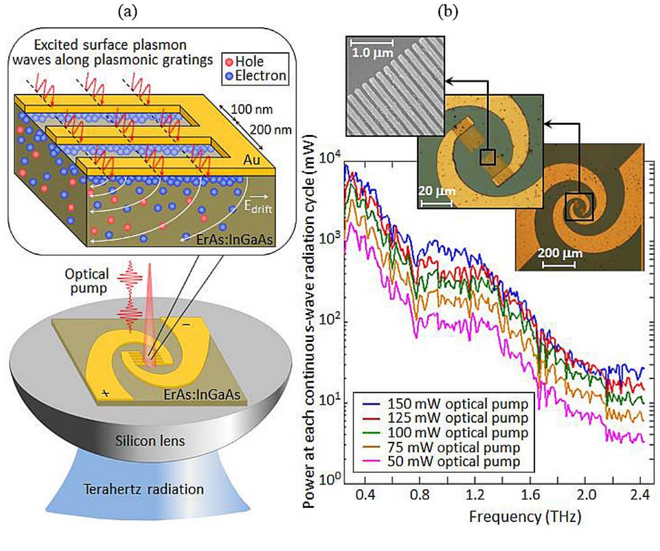

Fig. 8. (a) Schematic of a plasmonic photomixer fabricated on an ErAs:InGaAs substrate. (b) Radiated terahertz power from the plasmonic photomixer as a function of frequency for a radiation duty cycle of 2%, pump modulation frequency of 1 MHz, photomixer bias voltage of 10 V, and average optical pump power ranging from 50 to 150 mW [50]. Inset shows the scanning electron and optical microscope images of the plasmonic photomixer.

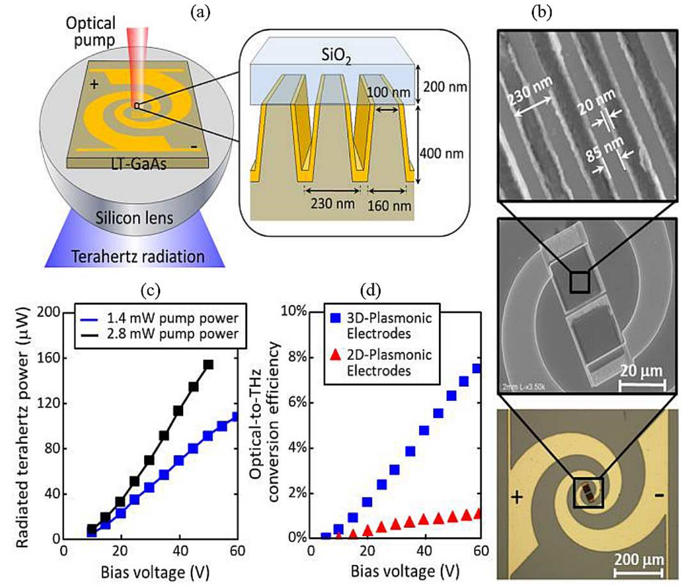

Fig. 9. Schematic and scanning electron microscope images of a photoconductive terahertz source with three-dimensional high-aspect ratio plasmonic contact electrode gratings are shown in (a) and (b), respectively. Radiated terahertz power as a function of optical pump power and bias voltage and optical-to-terahertz conversion efficiency in comparison with a similar photoconductive terahertz source with two-dimensional plasmonic contact electrode gratings are shown in (c) and (d), respectively [54].

a record-high radiation power of 0.8 mW has been achieved at 1 THz within each continuous-wave radiation cycle [Fig. 8(b)] [50].

F. Photoconductive Sources Based on Three-Dimensional Plasmonic Contact Electrode Gratings

As discussed in the previous sections, incorporating nano-plasmonic contact electrodes in photoconductive terahertz devices can significantly enhance the photoconductor quantum efficiency by concentrating a larger fraction of the incident pump photons near the device contact electrodes. This enhancement mechanism has been widely used in various photoconductive terahertz devices with a variety of device architectures and operational settings, demonstrating significant enhancements in the radiation power and detection sensitivity of photoconductive terahertz sources and detectors, respectively. Most of the demonstrated photoconductive terahertz devices based on nano-plasmonic contact electrodes have utilized two-dimensional nanostructures fabricated on the surface of the photo-absorbing semiconductor substrate. By use of two-dimensional nano-plasmonic contact electrodes, the concentration of the photocarriers within the device active area is enhanced for the photocarriers that are generated near the surface of the photo-absorbing semiconductor substrate. However, the device efficiency is still limited by the photocarriers generated deeper in the photo-absorbing substrate.

To address this limitation, a photoconductive terahertz source based on three-dimensional nano-plasmonic contact electrodes embedded inside the photo-absorbing substrate has been demonstrated. A logarithmic spiral antenna has been used for this study and the photoconductive terahertz source has been fabricated on a LT-GaAs substrate [Fig. 9(a)]. High-aspect ratio metallic gratings have been used for the three-dimensional plasmonic contact electrodes and have been designed to excite the fourth-order TEM guided mode of the subwavelength slab waveguides formed by the metallic gratings in response to a TM-polarized optical pump at 800 nm wavelength [42], [52]. This enables efficient coupling of 70% of the 800 nm optical pump into LT-GaAs nanostructures with 400 nm depth inside the substrate [Fig. 9(b)] [53]. The radiated terahertz power from the photoconductive terahertz source with three-dimensional plasmonic contact electrodes has been characterized [Fig. 9(c)] and compared with a similar photoconductive terahertz source with two-dimensional plasmonic contact electrodes [Fig. 9(d)]. Up to one order of magnitude higher optical-to-terahertz conversion efficiencies have been achieved by use of the three-dimensional plasmonic contact electrodes. Broadband terahertz radiation power levels as high as 105 μW have been demonstrated in the 0.1–2 THz frequency range in response to a 1.4 mW optical pump, exhibiting a record-high optical-to-terahertz power conversion efficiency of 7.5% [54].

III. Conclusion

In summary, an overview of some of the recent advancements in terahertz optoelectronic devices based on optical nano-antennas and nano-plasmonic light concentrators is presented. The use of nano-antennas and nano-plasmonic structures has proven to be very effective in enhancing the radiation power and detection sensitivity of photoconductive terahertz sources and detectors, respectively. This is because of the unique capability of nano-antennas and nano-plasmonic structures in manipulating the concentration of the photocarriers near the photoconductor contact electrodes, allowing a larger number of the photocarriers to reach the photoconductor contact electrodes within a terahertz oscillation cycle to efficiently contribute to terahertz radiation and detection. The role of nano-antennas and nano-plasmonic light concentrators in enhancing the efficiency of photoconductive terahertz devices is universal and can be employed in various types of photoconductive terahertz source/detector architectures with different types of terahertz radiating/receiving antennas, photo-absorbing substrates, and optical pump wavelengths in both pulsed and continuous-wave operation. Additionally, various types of two-dimensional and three-dimensional nano-plasmonic structures can be utilized to enhance the performance of photoconductive terahertz sources and detectors.

The use of nano-antennas and nano-plasmonic structures can also eliminate the need for short-carrier lifetime semiconductors, which have lower carrier mobilities and thermal conductivities compared to high quality crystalline semiconductors [55]. This would have a significant impact on future high efficiency photoconductive terahertz sources and detectors used in time-domain and frequency-domain terahertz imaging and spectroscopy systems. It could also lead to a new generation of photoconductive terahertz sources and detectors based on photo-absorbing semiconductors with unique functionalities (e.g., graphene-based photoconductive optoelectronics that benefit from superior carrier mobility and GaN-based photoconductive optoelectronics that benefit from superior thermal conductivity).

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REFERENCES

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nat. Photon.*, vol. 1, pp. 97–105, 2007.

[2] D. G. Rowe, "Terahertz takes to the stage," *Nat. Photon.*, vol. 1, pp. 75–77, Feb. 2007.

[3] D. Grischkowsky, S. Keiding, M. van Exter, and C. Fattinger, "Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors," *J. Opt. Soc. Amer. B*, vol. 7, no. 2006, 1990.

[4] D. M. Mittleman, R. H. Jacobsen, R. Neelamani, R. G. Baraniuk, and M. C. Nuss, "Gas sensing using terahertz time-domain spectroscopy," *J. Appl. Phys. B*, vol. 67, no. 3, 1998.

[5] K. Kawase, Y. Ogawa, Y. Watanabe, and H. Inoue, "Non-destructive terahertz imaging of illicit drugs using spectral fingerprints," *Opt. Express*, vol. 11, no. 20, pp. 2549–2554, Oct. 2003.

[6] R. M. Woodward, V. P. Wallace, D. D. Arnone, E. H. Linfield, and M. Pepper, "Terahertz pulsed imaging of skin cancer in the time and frequency domain," *J. Biol. Phys.*, vol. 29, pp. 257–261, Jun. 2003.

[7] D. D. Arnone, C. Ciesla, and M. Pepper, "Terahertz imaging comes into view," *Phys. World*, pp. 35–40, Apr. 2000.

[8] L. L. Van Zandt and V. K. Saxena, "Millimeter-microwave spectrum of DNA: Six predictions for spectroscopy," *Phys. Rev. A*, vol. 39, pp. 2672–2674, Mar. 1989.

[9] J. F. Federici *et al.*, "THz imaging and sensing for security applications-explosives, weapons and drugs," *Semicond. Sci. Technol.*, vol. 20, pp. S266–S280, Jul. 2005.

[10] M. C. Kemp, P. F. Taday, B. E. Cole, J. A. Cluff, A. J. Fitzgerald, and W. R. Tribe, "Security applications of terahertz technology," in *Proc. SPIE*, Jul. 2003, vol. 5070, pp. 44–52.

[11] M. Nagel, M. Forst, and H. Kurz, "THz biosensing devices: Fundamentals and technology," *J. Phys. Condensed Matter.*, vol. 18, no. 18, pp. S601–S618, Apr. 2006.

[12] D. Van der Weide, J. Murakowski, and F. Keilmann, "Gas-absorption spectroscopy with electronic terahertz techniques," *IEEE Trans. Microw. Theory Techn.*, vol. 48, no. 4, pp. 740–743, Apr. 2000.

[13] N. Nagai, T. Imai, R. Fukasawa, K. Kato, and K. Yamauchi, "Analysis of the intermolecular interaction of nanocomposites by THz spectroscopy," *Appl. Phys. Lett.*, vol. 85, pp. 4010–4012, Nov. 2004.

[14] P. Siegel, "Terahertz technology in biology and medicine," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 10, pp. 2438–2447, Oct. 2004.

[15] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting Hertzian dipoles," *Appl. Phys. Lett.*, vol. 45, pp. 284–286, May 1984.

[16] S. Preu, G. H. Dohler, S. Malzer, L. J. Wang, and A. C. Gossard, "Tunable, continuous-wave Terahertz photomixer sources and applications," *J. Appl. Phys.*, vol. 109, p. 061301, Mar. 2011.

[17] J. E. Bjarnason *et al.*, "ErAs:GaAs photomixer with two-decade tunability and 12 uW peak output power," *Appl. Phys. Lett.*, vol. 85, pp. 3983–3985, Nov. 2004.

[18] M. Jarrahi and T. H. Lee, "High power tunable terahertz generation based on photoconductive antenna arrays," in *IEEE Microw. Symp. Dig.*, 2008, pp. 391–394.

[19] E. Peytavit *et al.*, "Milliwatt-level output power in the sub-terahertz range generated by photomixing in a GaAs photoconductor," *Appl. Phys. Lett.*, vol. 99, p. 223508, Nov. 2011.

[20] H. Roehle *et al.*, "Next generation 1.5 μm terahertz antennas: Mesa-structuring of InGaAs/InAlAs photoconductive layers," *Opt. Express*, vol. 18, pp. 2296–2301, Feb. 2010.

[21] Z. D. Taylor, E. R. Brown, and J. E. Bjarnason, "Resonant-optical-cavity photoconductive switch with 0.5% conversion efficiency and 1.0 W peak power," *Opt. Lett.*, vol. 31, pp. 1729–1731, Jun. 2006.

[22] M. Jarrahi, "Terahertz radiation-band engineering through spatial beam-shaping," *Photon. Technol. Lett.*, vol. 21, pp. 830–832, Jul. 2009.

[23] M. Beck *et al.*, "Impulsive terahertz radiation with high electric fields from an amplifier-driven large-area photoconductive antenna," *Opt. Express*, vol. 18, pp. 9251–9257, Apr. 2010.

[24] S. Preu, M. Mittendorff, H. Lu, H. B. Weber, S. Winnerl, and A. C. Gossard, "1550 nm ErAs:In(Al)GaAs large area photoconductive emitters," *Appl. Phys. Lett.*, vol. 101, p. 101105, Sep. 2012.

[25] Y. Cai *et al.*, "Coherent terahertz radiation detection: Direct comparison between free-space electro-optic sampling and antenna detection," *Appl. Phys. Lett.*, vol. 73, pp. 444–446, 1998.

[26] F. G. Sun, G. A. Wagoner, and X.-C. Zhang, "Measurement of free-space terahertz pulses via long-lifetime Photoconductors," *Appl. Phys. Lett.*, vol. 67, pp. 1656–1658, 1995.

[27] J. F. O'Hara, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Enhanced terahertz detection via ErAs:GaAs nanoisland superlattices," *Appl. Phys. Lett.*, vol. 88, p. 251119, 2006.

[28] M. Tani, K.-S. Lee, and X.-C. Zhang, "Detection of terahertz radiation with low-temperature-grown GaAs-based photoconductive antenna using 1.55 μm probe," *Appl. Phys. Lett.*, vol. 77, pp. 1396–1398, 2000.

[29] T.-A. Liu, M. Tani, M. Nakajima, M. Hangyo, and C.-L. Pan, "Ultrabroadband terahertz field detection by photoconductive antennas based on multi-energy arsenic-ion-implanted GaAs and semi-insulating GaAs," *Appl. Phys. Lett.*, vol. 83, pp. 1322–1324, 2003.

[30] M. Suzuki and M. Tonouchi, "Fe-implanted InGaAs photoconductive terahertz detectors triggered by 1.56 μm femtosecond optical pulses," *Appl. Phys. Lett.*, vol. 86, p. 163504, 2005.

[31] T.-A. Liu *et al.*, "Ultrabroadband terahertz field detection by proton-bombarded InP photoconductive antennas," *Opt. Express*, vol. 12, pp. 2954–2959, 2004.

[32] E. Castro-Camus, J. Lloyd-Hughes, M. B. Johnston, M. D. Fraser, H. H. Tan, and C. Jagadish, "Polarization-sensitive terahertz detection by multicontact photoconductive receivers," *Appl. Phys. Lett.*, vol. 86, p. 254102, 2005.

[33] F. Peter, S. Winnerl, S. Nitsche, A. Dreyhaupt, H. Schneider, and M. Helm, "Coherent terahertz detection with a large-area photoconductive antenna," *Appl. Phys. Lett.*, vol. 91, pp. 40–42, 2007.

[34] S. Liu, X. Shou, and A. Nahata, "Coherent detection of multiband terahertz radiation using a surface plasmon-polariton based photoconductive antenna," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 2, pp. 412–415, Nov. 2011.

[35] C. W. Berry and M. Jarrahi, "Terahertz generation using plasmonic photoconductive gratings," *New J. Phys.*, vol. 14, p. 105029, Oct. 2012.

[36] C. W. Berry, N. Wang, M. R. Hashemi, M. Unlu, and M. Jarrahi, "Significant performance enhancement in photoconductive terahertz optoelectronics by incorporating plasmonic contact electrodes," *Nat. Commun.*, vol. 4, p. 1622, Mar. 2013.

[37] S. Park, K. H. Jin, M. Yi, J. C. Ye, J. Ahn, and K. Jeong, "Enhancement of terahertz pulse emission by optical nanoantenna," *ACS Nano*, vol. 6, pp. 2026–2031, 2012.

[38] S. Park, Y. Choi, Y. Oh, and K. Jeong, "Terahertz photoconductive antenna with metal nanoislands," *Opt. Express*, vol. 20, pp. 25530–25535, 2012.
[39] C. W. Berry and M. Jarrahi, "Plasmonically-enhanced localization of light into photoconductive antennas," in *Proc. Conf. Lasers and Electro-Optics*, 2010, CFI2.
[40] C. W. Berry and M. Jarrahi, "Ultrafast photoconductors based on plasmonic gratings," in *Proc. Int. Conf. Infrared, Millim. THz Waves*, 2011.
[41] C. W. Berry, M. R. Hashemi, M. Unlu, and M. Jarrahi, "Design, fabrication, and experimental characterization of plasmonic photoconductive terahertz emitters," *J. Visual. Experiments*, vol. 77, p. e50517, 2013.
[42] B.-Y. Hsieh and M. Jarrahi, "Analysis of periodic metallic nano-slits for efficient interaction of terahertz and optical waves at nano-scale dimensions," *J. Appl. Phys.*, vol. 109, p. 084326, 2011.
[43] C. W. Berry and M. Jarrahi, "Principles of impedance matching in photoconductive antennas," *J. Infrared, Millim. THz Waves*, vol. 33, pp. 1182–1189, 2012.
[44] C. W. Berry, M. R. Hashemi, and M. Jarrahi, "Generation of high power pulsed terahertz radiation using a plasmonic photoconductive emitter array with logarithmic spiral antennas," *Appl. Phys. Lett.*, vol. 104, p. 081122, 2014.
[45] N. Wang, M. R. Hashemi, and M. Jarrahi, "Plasmonic photoconductive detectors for enhanced terahertz detection sensitivity," *Opt. Express*, vol. 21, p. 17221, Jul. 2013.
[46] N. Wang and M. Jarrahi, "Noise analysis of photoconductive terahertz detectors," *J. Infrared, Millim. THz Waves*, vol. 34, pp. 519–528, 2013.
[47] B. Heshmat *et al.*, "Nanoplasmonic terahertz photoconductive switch on GaAs," *Nano Lett.*, vol. 12, pp. 6255–6259, Nov. 2012.
[48] N. T. Yardimci, S.-H. Yang, C. W. Berry, and M. Jarrahi, "High power terahertz generation using large area plasmonic photoconductive emitters," *IEEE Trans. THz Sci. Technol.*, vol. 5, no. 2, pp. 223–229, Mar. 2015.
[49] N. T. Yardimci, S.-H. Yang, C. W. Berry, and M. Jarrahi, "Plasmonics enhanced terahertz radiation from large area photoconductive emitters," in *Proc. IEEE Photon. Conf.*, San Diego, CA, Oct. 12–16, 2014.
[50] C. W. Berry, M. R. Hashemi, S. Preu, H. Lu, A. C. Gossard, and M. Jarrahi, "High power terahertz generation using 1550 nm plasmonic photomixers," *Appl. Phys. Lett.*, vol. 105, p. 011121, 2014.
[51] C. W. Berry, M. R. Hashemi, S. Preu, H. Lu, A. C. Gossard, and M. Jarrahi, "Plasmonics enhanced photomixing for generating continuous-wave frequency-tunable terahertz radiation," *Opt. Lett.*, vol. 39, pp. 4522–4524, 2014.
[52] B.-Y. Hsieh, N. Wang, and M. Jarrahi, "Toward ultrafast pump-probe measurements at the nanoscale," *Opt. Photon. News*, vol. 22, p. 48, 2011.
[53] S.-H. Yang and M. Jarrahi, "Enhanced light-matter interaction at nanoscale by utilizing high aspect-ratio metallic gratings," *Opt. Lett.*, vol. 38, pp. 3677–3679, 2013.
[54] S. H. Yang, M. R. Hashemi, C. W. Berry, and M. Jarrahi, "7.5% optical-to-terahertz conversion efficiency offered by photoconductive emitters with three-dimensional plasmonic contact electrodes," *IEEE Trans. THz Sci. Technol.*, vol. 4, pp. 575–581, Sep. 2014.
[55] S. C. Corzo-Garcia, M. Alfaro, and E. Castro-Camus, "Transit time enhanced bandwidth in nanostructured terahertz emitters," *J. Infrared, Millim. THz Waves*, Sep. 2014.

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