Tailoring the Thickness-Dependent Optical Properties of Conducting Nitrides and Oxides for Epsilon-Near-Zero-Enhanced Photonic Applications

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The unique properties of the emerging photonic materials, conducting nitrides and oxides, especially their tailorability, large damage thresholds, and, importantly, the so-called epsilon-near-zero (ENZ) behavior, have enabled novel photonic phenomena spanning optical circuitry, tunable metasurfaces, and nonlinear optical devices. This work explores direct control of the optical properties of polycrystalline titanium nitride (TiN) and aluminum-doped zinc oxide (AZO) by tailoring the film thickness, and their potential for ENZ-enhanced photonic applications. This study demonstrates that TiN–AZO bilayers support Ferrell–Berreman modes using the thickness-dependent ENZ resonances in the AZO films operating in the telecom wavelengths spanning from 1470 to 1750 nm. The bilayer stacks also act as strong light absorbers in the ultraviolet regime using the radiative ENZ modes and the Fabry–Perot modes in the constituent TiN films. The studied Berreman resonators exhibit optically induced reflectance modulation of 15% with picosecond response time. Together with the optical response tailorability of conducting oxides and nitrides, using the field enhancement near the tunable ENZ regime can enable a wide range of nonlinear optical phenomena, including all-optical switching, time refraction, and high-harmonic generation.

1. Introduction

In optical device design, tailoring the optical response of constituent materials is important for achieving the desired functionalities. This makes it important to develop methods of controlling the optical properties of technologically relevant materials. Titanium nitride is a promising material for nanophotonic applications because of its good plasmonic properties,[1] complementary metal-oxide-semiconductor (CMOS) compatibility,[2] tailorability,[3,4] versatility of fabrication techniques,[5–7] and high laser- and thermal tolerance.[8–10] These attractive features have led to its utilization in high-temperature photovoltaics,[11] optical circuitry,[12,13] nonlinear optical devices,[8,14] and many other practical applications. Similarly, transparent conducting oxides (TCOs) form another class of optical materials for dynamically controlled nanophotonics spanning optical switching,[15] electroabsorption modulators,[16,17] tunable metasurfaces,[18,19] and nonlinear experiments employing epsilon-near-zero (ENZ) physics.[20–24] It is mainly the strong field-enhancement at the ENZ regime that has recently made this class of materials so popular for novel applications that now include ultrafast switching,[25–27] tunable broadband light absorption,[28–31] enhanced second-harmonic[32] and high harmonic[33] generation.

For these technologically relevant materials, the optical properties can be controlled during growth by varying deposition conditions. For example, the properties of titanium nitride can be tailored by fine-tuning the temperature, gas ratio, and even postdeposition annealing.[5,14,15] The optical properties and the ENZ resonances of conducting oxides can also be altered by varying the growth conditions, namely, the gas ratio, the dopant concentrations, or postdeposition annealing.[5,17,36,37] However, a simpler method of tailoring such conducting oxides and nitrides is often overlooked. The conductivity of materials, an intrinsic material property, is strongly affected by the film thickness due to changes in the carrier concentration, crystalline properties, and surface roughness,[38–41] especially for thin films. It stands to reason that film thickness should also play a role in the optical property of conducting materials, and in
turn, be used to control device characteristics. This work explores the thickness-dependence of the optical properties of polycrystalline titanium nitride (TiN) and aluminum-doped zinc oxide (AZO) and how these materials can be tailored for select passive and dynamic photonic applications, especially those utilizing the ENZ properties of the constituent thin films.

Titanium nitride in its epitaxial form has been utilized in absorbers,[9] waveguiding,[12,13] refractory plasmonics,[8–10] plasmonic nanoparticle lattices,[42] and physics with ultrathin films.[43] However, epitaxial film growth requires lattice-matched substrates, which limits their application in an industry-compatible setting.[44] This difficulty makes it essential to grow and characterize optical-quality films of titanium nitride on non-lattice-matched substrates. We develop low-loss, polycrystalline films of titanium nitride on silicon by reactive magnetron sputtering. Furthermore, we show that the optical properties of the films have a strong dependence on thickness, which adds a way to tailor them. We investigate the cause of the thickness-dependent optical properties through spectroscopic ellipsometry, atomic force microscopy, and transmission electron microscopy, connecting the optical properties to their structural properties. We grow aluminum-doped zinc oxide (AZO) by pulsed laser deposition on the as-grown titanium nitride films. The AZO films show lower losses in the ENZ regimes than films grown by other methods such as sputtering and atomic layer deposition.[45,46] Their optical properties and the ENZ resonances can be tailored during fabrication by varying the thickness.

Building upon the demonstrated adjustability of the TiN and AZO properties, we demonstrate AZO/TiN bilayers where the AZO film is grown on the reflective TiN. Such structures form tailorable, so-called Ferrell–Berremares (FB) resonators with the absorption wavelength that can be varied by controlling the TiN thickness. The proposed devices can operate in a wavelength range from 1470 to 1750 nm, covering the technologically important telecommunication wavelength range. We show that TiN also exhibits both Fabry–Pérot type reflectance dips that vary with the layer thickness and Ferrell–Berremares dips near its ENZ point. As a proof of concept of a dynamic, tunable device, we demonstrate all-optical switching of the resonators using an interband pump, showing picosecond relaxation times. Understanding the thickness-dependent optical properties of robust, tailorable conducting films will establish a design framework for optimized optical devices[47,48] that could be extended to the important area of the inverse photonic design for globally optimized photonic applications.[49,50]

2. Tailoring TiN and AZO Optical Response by Varying the Thickness

2.1. Titanium Nitride on Silicon

To investigate the effect of thickness on the optical response of polycrystalline TiN films, we grew TiN films of several thicknesses on silicon by DC reactive magnetron sputtering at elevated temperatures. This method was utilized to produce optical grade TiN by other groups.[51–53] Alternative techniques of growing TiN include pulsed laser deposition[42,54] and atomic layer deposition.[51] Section S1 (Supporting Information) has details of the growth procedure.

We measured the optical properties of the TiN films with spectroscopic ellipsometry, and fitted them with a Drude–Lorentz model,[55] with one free electron term and two Lorentz oscillator terms with the resonance positions at higher energy levels. For the visible wavelengths, the Lorentzian terms govern the response, whereas for longer wavelengths the free electron oscillations become dominant, i.e., the Drude term defines the overall response. The Drude–Lorentz model of the TiN dielectric function is given as follows

\[
\varepsilon = \varepsilon_i + i\varepsilon_2 = \varepsilon_i - \frac{A_0}{(\omega_0)^2 + i\omega B_0} = \frac{1}{\varepsilon_i} - \sum_{\text{osc}} \frac{A_n}{(\omega_0 - \omega_n + i\Gamma_n)^2} + \frac{A_0}{(\omega_0 - \omega_D + i\Gamma_D)^2}
\]

where \(\omega\) is the angular frequency, \(\hbar\) is the reduced Planck constant, \(\varepsilon_i\) is the background permittivity, \(A_0 [\text{eV}^2]\) is the square of the plasma frequency, and \(B_0 [\text{eV}]\) is the Drude damping coefficient. The Drude term is summed up with two Lorentz terms with \(n_{th}\) oscillator strength \(A_n [\text{eV}^2]\), broadening \(B_n [\text{eV}]\), and resonance position \(\omega_n [\text{eV}]\). Section S1 (Supporting Information) contains the measurement details and the model parameters.

In the telecommunication range, the contribution of free electrons, represented by the Drude term, strongly governs the optical response. Then, the real and the imaginary parts of the permittivity can be written separately as

\[
\varepsilon_1 = \varepsilon_i - \frac{A_0}{(\omega_0)^2 + B_0} = \frac{\varepsilon_0}{\omega_0^2 + B_0}
\]

\[
\varepsilon_2 = \frac{A_0 B_0}{\hbar^2 (\omega_0)^2 + B_0^2}
\]

where \(\varepsilon_0\) denotes the net contribution of the Lorentz oscillators with background permittivity \(\varepsilon_i\).

The dielectric function of TiN films with different thicknesses are plotted in Figure 1.

At first, as the thickness increases up to 25 nm, the slope of the real part of the TiN dielectric function becomes steeper, implying increased metallicity (see Figure 1a). The figure indicates that when the thickness is approaching 60 nm, the change of the real part is saturating. For the imaginary part of the TiN dielectric function (\(\varepsilon_2\)) this dependence is different; as the film thickness decreases from 130 to 10 nm, we observe an increase that indicates increasing absorptive losses (Figure 1b). Figure 1c plots the so-called plasmonic figure of merit (FOM) of the films, defined as the absolute value of the ratio of the real part of the permittivity to the imaginary part.[54–56] The grown TiN films have figure of merits better than the majority of the reported polycrystalline films, and comparable to that of some epitaxial films[42,54,57–61] (see also Table S5, Supporting Information).

To understand the change in the optical response with the thickness, we investigated the crystalline structure of the TiN and its permittivity model. The plasma frequency increases for thicknesses up to 25 nm then starts decreasing (Figure 1d). An increase in the plasma frequency causes both the real and the imaginary part of the permittivity to increase.

The plasma frequency is related to carrier concentration and the effective mass of the electrons through the equation

\[
\hbar^2 \omega_0 = m^* \varepsilon_0 = \varepsilon_i \frac{N}{\sqrt{m^* \varepsilon_0}}\]

The plasma frequency of the fabricated polycrystalline films is lower (\(\omega_0\) between 43 and 51.6 [eV])
than that of epitaxial titanium nitride films ($A_0 \approx 58$ (eV)$^2$) reported in previous studies.[13,62] This is because of the columnar growth of the polycrystalline films seen from TEM (Figure S1, Supporting Information), which reduces the density of TiN, and the creation of many grain boundaries, through which oxygen diffuses into the lattice, lowering the carrier density further.[63–65]

The 10 nm-thick films have the highest damping factors attributed to the increased collisions of electrons with the surface. A similar effect was observed by Shah et al. in a previous study, where the damping factor of TiN thin films increased with decreasing thickness.[43] AFM images (Figure S2, Supporting Information) show that the thicker films have more well-defined and bigger grains. For thicker films, the damping factor generally decreases due to increased grain size, leading to a decreased collision of carriers with the grain boundaries. The films have a surface roughness of less than $\approx 3.5$ nm, which is higher than in atomically flat epitaxial films, yet comparable to polycrystalline films reported previously.[42,54] Overall, the dielectric function of the studied TiN films shows a strong dependence on the thickness, adding a critical degree of control over their optical response.

2.2. Al-Doped Zinc Oxide Grown on Titanium Nitride Films

We deposited aluminum-doped zinc oxide on optically thick TiN films using pulsed laser deposition (PLD) with a 2% AZO target at a temperature of 120 °C. We grew film thicknesses spanning from 27 to 63 nm. The 27–43 nm films are grown on 60 nm TiN, and the 57 and 63 nm films are grown on 130 nm TiN. The TEM image of the 43 nm AZO film is given in Section S3 (Supporting Information). For the dielectric functions of AZO, we used a Drude–Lorentz model with a single Lorentz oscillator. Section S3 (Supporting Information) contains the model parameters. Figure 2 shows the optical properties of the fabricated AZO films.

The ENZ points of the films show a strong blueshift with increasing thicknesses, starting from 1750 nm for the 27 nm-thick films, and reaching the lowest value of 1470 nm for the 63 nm-thick film. The optical losses increase with thickness up to 57 nm then start to saturate for higher thicknesses. With the increasing thickness, the size of the crystalline domains increases, as seen from atomic force microscopy study (Figure S3, Supporting Information). Thinner films also have more surface defects that can trap electrons and decrease the carrier concentration. As a result, the carrier concentration increases with increasing thickness,[66] and so does the plasma frequency (Figure 3c).[67–69] The thicker films have larger grain sizes with a lower surface-to-volume ratio that decreases the scattering channels for electrons.[66] Similar increases in the carrier density and the Hall-mobility with increasing thicknesses of AZO have been observed via conductivity studies for transparent electrode applications by Luka et al.[66] Overall, the thicker films are more metallic and the ENZ frequency blueshifts with increasing thickness. The losses increase with the thickness because of the increasing carrier densities, increasing the plasma frequency but the losses corresponding to the ENZ points decreases with increasing thickness, because of the blueshifted ENZ.

Figure 1. a) Real part of permittivity of TiN on Si versus thickness. b) Imaginary permittivity of TiN on Si versus thickness. c) Plasmonic figure of merit versus thickness. d) Plasma frequency ($A_0$) and Drude damping ($B_0$) versus the film thickness.
3. Tailoring TiN–AZO Bilayer Stacks for Double-Resonant Ferrell–Berreman Absorbers

We utilize the thickness-tailorable ENZ points of the conducting films to develop wavelength-selective absorbers. In the epsilon-near-zero regime, materials have diminishingly small dielectric permittivity that causes various singularities in their optical responses.\[^{70}\] In this region, strong light–matter interactions induced by slow-light effects and field-intensity enhancement have enabled applications in nonlinearity enhancement,\[^{22,23,71}\] femtosecond optical switching,\[^{27,72}\] time refraction,\[^{73–75}\] optical time reversal,\[^{76}\] and extracting hot electron dynamics in materials.\[^{77}\] Ultrathin ENZ films demonstrate unique absorption resonances for p-polarized light in their ENZ region, termed the FB modes and the ENZ modes. As the film thickness decreases, the bound surface modes on the upper and the lower interface of the film start interacting with each other, hybridizing into symmetric and antisymmetric modes.\[^{78}\] Eventually, the symmetric mode forms a flat dispersion band near the ENZ frequency as the thickness is further reduced. This bound resonance is called the ENZ mode.\[^{79,80}\] The radiative modes called the Ferrell–Berreman modes are situated in the radiative region occur due to the plasma oscillations in metallic films,\[^{81,82}\] and the excitation of the longitudinal optical phonon in dielectric films.\[^{83}\] FB resonances have the further advantage of direct excitation from free space without the need for an additional structure enabling low-cost, lithography-free fabrication. ITO,\[^{29}\] CdO,\[^{31}\] and AZO\[^{84}\] have been recently utilized in applications such as broadband absorption and polarization switching.

A FB resonator comprises two parts—a robust back-reflector, and an ENZ thin film. The resonance wavelength of the FB resonator depends on the optical properties of the ENZ film. The TiN–AZO bilayer stacks form a double-resonant FB device, with two dips near the ENZ regions of TiN and AZO for p-polarized light at an angle of incidence of 50° (Figure 3a). As the AZO ENZ point shows a large variance with the changing thickness, the FB dip at the telecom frequencies can be tailored by changing the thickness of the AZO films. Near these ENZ points, the loss (imaginary permittivity) is around 0.6. Near the telecommunication wavelength, the reflectance spectrum for s-polarized light is flat (Figure S5, Supporting Information).

The AZO layer is almost transparent in the visible wavelengths and the structure can be simplified to a thin TiN layer on a reflective silicon substrate. The TiN ENZ point shows a smaller variance (<10 nm) with the changing thickness. It has larger losses (imaginary part of the permittivity around 3), resulting in a broad FB dip near 480 nm that is not affected by changing the TiN thickness (Figure 3b). On the other hand, near the visible wavelengths, s-polarized light shone on TiN shows strong shifts with the thickness variance, indicating the excitation of Fabry–Pérot mode (Figure 3c). This approach shows how utilizing multilayer stacks and engineering their properties individually can be used to tune the broadband characteristics of the overall structure. We also included the ENZs
of TiN and AZO and their corresponding losses in Tables S3 and S4 (Supporting Information).

Previously, lithography-free absorbers have been studied for a variety of applications spanning colors,[85–87] electrical modulators,[30] and polarization switches.[26] To examine the efficacy of the grown films for use in absorbers, we investigated the effect of the angle of incidence on the spectrum theoretically using a transfer matrix method (TMM) model,[88] using the experimentally obtained dielectric properties of the thin films. Figure 3d shows the absorption of the films with respect to the angle of incidence and wavelength. The films show near-perfect absorption around the ENZ region for the larger angles of incidences. The peaks get narrower as the thickness increases because of decreasing losses, desirable for switching applications. Since the absorption is directly related to the intensity enhancement, shown in prior studies by Anopchenko and Gurung et al.[89,90] it would be possible to observe high field intensities inside the AZO film, with potential applications in nonlinear optics spanning time refraction,[75] and optical time-reversal,[91] and high-harmonic generation[92] using robust ENZ films.

The depth and the quality factor of the resonances depend on many factors in addition to the material losses, such as the angle of incidence, thickness, and the backreflector.[93] As the angle increases the coupling strength to FB modes increases, therefore increasing the attainable maximum absorption.[79] Also, lower losses around the ENZ correspond to sharper peaks with both narrower features and higher maximum values. Thicker AZO films have their ENZ frequency at lower wavelengths, with smaller losses. Hence, perfect absorption is attainable with thicker films at larger angles of incidences.

A more detailed quantitative analysis of the effect of losses requires a thorough analytical study, considering the experimental conditions, the pump type, and material thickness, which was performed in a separate tutorial review.[93] Since the absorptive losses are intrinsic to the material properties, they are expected to be in the same ballpark for AZO grown on different substrates and with different techniques, although slight improvements are expected for epitaxial films. However, even with these losses, epsilon-near-zero enhanced effects such as large reflectance modulation[94] frequency...
translation,[95] addition of nonlinearities,[72] and negative refraction[96] are achievable. Thickness-tailoring provides an additional method of achieving such effects at different wavelengths, which is highlighted here, with the dynamic reflectance modulation as an example. We note here that the evolution of the optical properties with the thickness is strongly associated with the mode of growth of the films.[97] Thus, the thickness can be a design parameter only when using specific growth conditions.

4. Exploring TiN–AZO Bilayers for Dynamic Photonics

For a proof-of-concept demonstration of the as-grown films in photonic time-varying applications, we investigated the reflectance modulation of the 63 nm-thick AZO FB absorber with an interband pump—near-infrared (NIR) probe configuration. The pump at 325 nm wavelength is generated by passing a 70 fs, 800 nm pump laser through an OPA. The probe is generated by passing the pump through a sapphire crystal to generate a NIR supercontinuum probe. The pump is at normal incidence, while the probe is at an angle of incidence of 50° (Figure 4a). Upon excitation by the pump, free carriers generated in the AZO cause the ENZ to blueshift, resulting in broadband modulation of the reflectance spectrum. As the reflectance spectrum blueshifts due to decreasing refractive index, a positive change is seen to the blue end of the reflectance minimum, and a negative change is seen at the longer wavelengths. A reflectance change of 15% is seen at 1350 nm, at a pump fluence of 1.5 mJ cm$^{-2}$.

The relaxation time of the switching here is on the picosecond scale, with 90% of the signal decaying under 10 ps due to defect-assisted Shockley–Read–Hall mechanisms,[27,98] after which the modulation is dominated by slower, thermal effects (Figure 4b,c).[99] Active permittivity modulation of AZO with an applied optical pump may be useful for all-optical transistors[72] and other time-varying metasurface applications.[73,95,100] Deeper and faster modulation may be possible using intraband pumps working at larger angles near the FB resonance,[15,25] enabling stronger pump absorption.

5. Conclusion

We have investigated the thickness-dependent optical response of conducting nitrides and oxides, namely, plasmonic titanium nitride and aluminum-doped zinc oxide as a tailorable, industry-compatible, low-loss platform for passive and dynamic photonics. Specifically, we study the properties of low-loss, optical grade titanium nitride grown on the technologically relevant silicon substrate. The studied TiN films exhibit plasmonic properties that are better than any previously reported work of TiN on silicon, and in some instances, even better than epitaxial titanium nitride grown at lower temperatures.
For both TiN and AZO, we demonstrate that by controlling the thickness, the optical properties of the conducting films can be adjusted. For photonic device demonstrations, we grow aluminum-doped zinc oxide on the as-grown titanium nitride films. Furthermore, we show that the spectral window of the ENZ regime of the studied AZO films can be varied by almost 400 nm by changing the film thickness by ~40 nm, resulting in tailorable Ferrell–Berreman modes spanning the telecommunication wavelength range. Subsequently, we demonstrate strong absorbers utilizing the proposed AZO/TiN bilayers that use dual Ferrell–Berreman modes, one near the ENZ point of TiN and the other near that of the AZO film. To explore the feasibility of the materials for dynamic photonics, we demonstrate reflectance modulation in the studied AZO/TiN bilayers with pump–probe spectroscopy and show that the absorbance can be tuned at picosecond timescales in the near-infrared range. Since the FB mode only occurs for p-polarized light switching, this can enable active polarization control of the reflected light.

The thickness-dependent optical properties of low-loss conducting films can be employed to develop efficient, tailorable photonic devices including lithography-free light absorbers in the near-infrared to the mid-infrared regime, all-optical switches as well as nonlinear structures for high-harmonic generation.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
aluminum-doped zinc oxide, Berreman resonators, epsilon-near-zero materials, metasurfaces, tailorable absorbers, titanium nitride, transparent conducting oxides

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[1] P. Patsalas, N. Kalfagiannis, S. Kassavetis, Materials 2015, 8, 3128.
[2] D. C. Park, T. H. Cha, K. Y. Lim, H. J. Cho, T. K. Kim, S. A. Jang, Y. S. Suh, V. Misra, I. S. Yeo, J. S. Roh, J. W. Park, H. K. Yoon, Int. Electron Devices Meeting. Tech. Dig. (Cat. No.01CH37224), IEEE, Piscataway, NJ, USA 2001, https://doi.org/10.1109/IEDM.2001.979597.
[3] C.-C. Chang, J. Nogan, Z.-P. Yang, W. J. M. Kort-Kamp, W. Ross, T. S. Luk, D. A. R. Dalvit, A. K. Azad, H.-T. Chen, Sci. Rep. 2019, 9, 15287.
[4] M. Georgsson, A. Roos, C.-G. Ribbing, J. Vac. Sci. Technol., A 1998, 9, 2191.
[5] Y. Wang, A. Capretti, L. Dal Negro, Opt. Mater. Express 2015, 5, 2415.
[6] R. P. Sugavaneshwar, S. Ishii, T. D. Dao, A. Ohi, T. Nabatame, T. Nagao, ACS Photonics 2018, 5, 814.
[7] R. Secondo, V. Avrutin, U. Özgür, N. Kinsey, Conf. on Lasers and Electro-Optics, OSA, Washington, DC, USA 2018, p. JThA2.75.
[8] L. Gui, S. Bagheri, N. Strohfeldt, M. Hentschel, C. M. Zgrabik, B. Metzger, H. Linnenbank, E. L. Hu, H. Giessen, Nano Lett. 2016, 16, 5708.
[9] W. Li, U. Guler, N. Kinsey, G. V. Naik, A. Boltasseva, J. Guan, V. M. Shalaev, A. V. Kildishev, Adv. Mater. 2014, 26, 7959.
[10] K. Chaudhuri, U. Guler, S. I. Azzam, H. Reddy, S. Saha, E. E. Marinier, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, ACS Photonics 2020, 7, 472.
[11] M. Chirimamilla, A. Chirimamilla, Y. Yang, A. S. Roberts, P. K. Kristensen, K. Chaudhuri, A. Boltasseva, D. S. Sutherland, S. I. Bozhevolnyi, K. Pedersen, Adv. Opt. Mater. 2017, 5, 1700552.
[12] S. Saha, A. Dutta, N. Kinsey, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, ACS Photonics 2018, 5, 4423.
[13] N. Kinsey, M. Ferrera, G. V. Naik, V. E. Babicheva, V. M. Shalaev, A. Boltasseva, Opt. Express 2014, 22, 12238.
[14] N. Kinsey, A. A. Syed, D. Courtwright, C. DeVault, C. E. Bonner, V. I. Gavrilenko, V. M. Shalaev, D. J. Hagan, E. W. van Stryland, A. Boltasseva, Opt. Mater. Express 2015, 5, 2587.
[15] Y. Yang, K. Kelley, E. Sachet, S. Campione, T. S. Luk, J.-P. Maria, M. B. Sinclair, I. Brer, Nat. Photonics 2017, 11, 390.
[16] H. W. Lee, G. Papadakis, S. P. Burgos, A. Kriesch, R. P. Sugavaneshwar, S. Ishii, T. D. Dao, A. Ohi, T. Nabatame, T. Nagao, ACS Photonics 2020, 14, 6463.
[17] M. G. Wood, S. Campione, S. Parameswaran, T. S. Luk, J. R. Wendt, D. K. Serkland, G. A. Keeler, Optica 2018, 5, 233.
[18] M. K. Shiramesh, R. Sokhoyan, P. C. Wu, H. A. Atwater, P. C. Wu, H. A. Atwater, H. A. Atwater, ACS Nano 2020, 14, 6912.
[19] Y.-W. W. Huang, H. W. H. Lee, R. Sokhoyan, R. A. Pala, K. Thyagarajan, S. Han, D. P. Tsai, H. A. Atwater, Nano Lett. 2016, 16, 5319.
[20] M. Z. Alam, I. De Leon, R. W. Boyd, Science 2016, 352, 795.
[21] O. Reshef, I. de Leon, M. Z. Alam, R. W. Boyd, Nat. Rev. Mater. 2019, 4, 535.
[22] A. Capretti, L. D. Negro, N. Engheta, Y. Wang, Opt. Lett. 2015, 40, 1500.
[23] L. Caspani, R. P. M. Kaipurath, M. Clerici, M. Ferrera, T. Roger, J. Kim, N. Kinsey, M. Pietrzyk, A. di Falco, V. M. Shalaev, A. Boltasseva, D. Faccio, Phys. Rev. Lett. 2016, 116, 233901.
[24] E. Galiffi, J. Drancezewski, J. Pendry, R. Sapienza, R. Tirole, S. Maier, S. Vezzoli, T. Attavart, R. Sapienza, in Conf. on Lasers and Electro-Optics, OSA, Washington, DC, USA 2021, p. FMM5.6.
[25] J. Bohn, T. S. Luk, C. Tollerton, S. W. Hutchings, I. Brer, S. Horsley, W. L. Barnes, E. Hendry, Nat. Commun. 2021, 12, 1017.
[26] Y. Yang, K. Kelley, E. Sachet, S. Campione, T. S. Luk, J.-P. Maria, M. B. Sinclair, I. Brer, Nat. Photonics 2017, 11, 390.
[27] N. Kinsey, C. DeVault, J. Kim, M. Ferrera, V. M. Shalaev, A. Boltasseva, Optica 2015, 2, 616.
[28] V. Bruno, S. Vezzoli, C. Devault, T. Roger, M. Ferrera, A. Boltasseva, V. M. Shalaev, D. Faccio, Micromachines 2020, 11, 110.
[93] C. Fruhling, M. G. Ozlu, S. Saha, A. Boltasseva, V. M. Shalaev, Appl. Phys. B: Lasers Opt. 2022, 128, 34.
[94] N. Kinsey, C. DeVault, J. Kim, M. Ferrera, V. M. Shalaev, A. A. Boltasseva, Optica 2015, 2, 616.
[95] V. Bruno, S. Vezzoli, C. DeVault, E. Carnemolla, M. Ferrera, A. Boltasseva, V. M. Shalaev, D. Faccio, M. Clerici, Appl. Sci. 2020, 10, 1318.
[96] V. Bruno, C. DeVault, S. Vezzoli, Z. Kudyshev, T. Huq, S. Mignuzzi, A. Jacassi, S. Saha, Y. D. Shah, S. A. Maier, D. R. S. Cumming, A. Boltasseva, M. Ferrera, M. Clerici, D. Faccio, R. Sapienza, V. M. Shalaev, Phys. Rev. Lett. 2019, 124, 043902.
[97] P. Patsalas, S. Logothetidis, Surf. Coat. Technol. 2004, 180, 421.
[98] S. Saha, A. Dutta, C. T. DeVault, B. T. Diroll, R. D. Schaller, Z. A. Kudyshev, X. Xu, A. Kildishev, V. M. Shalaev, A. Boltasseva, Mater. Today 2021, 43, 27.
[99] P. Guo, R. D. Schaller, L. E. Ocola, B. T. Diroll, J. B. Ketterson, R. P. H. Chang, Nat. Commun. 2016, 7, 12892.
[100] E. Lustig, S. Saha, E. Bordo, C. DeVault, S. N. Chowdhury, Y. Sharabi, A. Boltasseva, O. Cohen, V. M. Shalaev, M. Segev, in Conference on Lasers and Electro-Optics, OSA, Washington, DC, USA 2021, p. FF2H.1.