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Electrically-Controlled Thermal Infrared Metamaterial Devices

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Abstract: We demonstrate electrically-controlled thermal mid-infrared metamaterials using depletion-type semiconductor devices. This electrical tuning is generally applicable to a variety of infrared metamaterials and plasmonic structures, which can find novel applications in chip-scale active infrared devices.
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Recently, optical metamaterials have attracted significant attention. Artificially tailored electromagnetic structures can exhibit exotic optical properties such as optical magnetism, negative refraction, sub-diffraction imaging, and cloaking. Active tuning of metamaterials is emerging as a natural next step in this burgeoning field. Tunable metamaterials also have potential for novel active devices such as optical switches, modulators, filters, and phase shifters. There have been several approaches for active tuning - e.g. with mechanical movement or stretching [1], reorientation in liquid crystals [2], and phase transitions in vanadium dioxide [3, 4]. However, electrical control based on semiconductor device architectures is more technologically appealing for practical, chip-scale devices. Here, we present electrically-controlled active tuning of mid-infrared metamaterials using depletion-type devices. The depletion width in an n-doped semiconductor epilayer changes with an electric bias, inducing a change of the permittivity of the substrate and leading to frequency tuning of the resonance. s

Figure 1 shows the images of the fabricated device. An n+ GaAs epilayer ($N_D = 5 \times 10^{18}$ cm^{-3}) were grown on a semi-insulating GaAs substrate by molecular beam epitaxy, followed by the growth of a 30 nm undoped $Al_{0.3}Ga_{0.7}As$ barrier layer. First, metal contacts were defined by optical lithography (Fig. 1(a)) and then a gold metamaterial layer was patterned by electron-beam lithography (Fig. 1(b)). The metamaterial layer was connected to the metal gate via electrical bus lines and worked as a metal gate too which induces the depletion width change in the n-doped epilayer. We chose a modified split-ring resonator (SRR) geometry [5] as our "meta-atom" because of its strong field enhancement in two gaps and the easiness for electrical connection. The gold SRR is designed to be resonant in the mid-IR ($\lambda_0 \sim 10$ μm). The transmission spectrum through the metamaterial layer shows a dip at the resonance frequency. By applying an electric bias and changing the depletion width in the substrate, we dynamically tune the frequency of this transmission minimum.

Transmission spectra of the fabricated metamaterial devices were measured at room temperature with a Fourier-transform infrared spectrometer (FTIR). Incident glow bar emission was polarized normal to the SRR gap to excite a resonance. The sample was biased (DC) during transmission measurements.

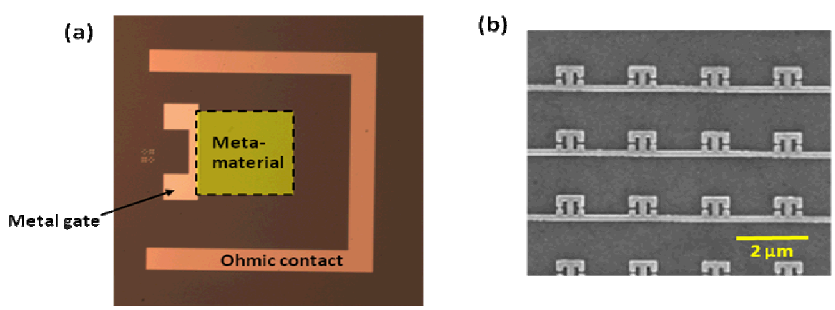

Fig. 1: (a) An optical microscope image of metal contacts (patterned using optical lithography). The outside contact is an ohmic contact, and the inner one is a metal gate contact which is connected to the active area (colored region). The size of the active (SRR) region is 1mm x 1mm. Both metal gate and ohmic contact are later wire-bonded to a chip-carrier for electric biasing. (b) A SEM image of SRR arrays (patterned using electron-beam lithography).

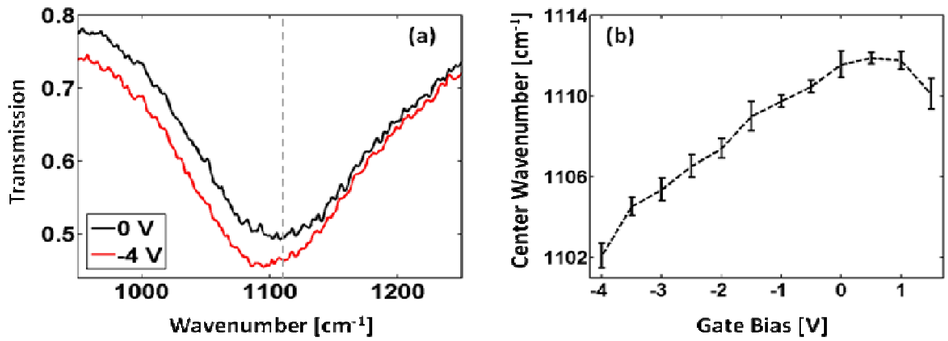

Fig. 2: (a) FTIR measurement of SRR transmission spectra for the gate bias V_G = 0 V and -4 V. The dotted vertical line is the center frequency of V_G = 0 V. We can see that the spectrum at V_G = -4 V is slightly red-shifted. (b) The Center frequency of the metamaterial transmission resonance vs. Gate bias. The error bar was obtained from the repetition of measurements.

Figure 2(a) shows a representative SRR transmission spectrum. As the reverse bias increased from 0 V to -4 V, the resonant transmission peak red-shifted. We also measured the resonant frequencies with gradually varying bias voltages. The center frequency was determined by fitting a gaussian curve to the FTIR spectra. The shift was small, but we can clearly see that it gradually red-shifts with a negative bias (Fig. 2(b)).

The dielectric constant of a semiconductor substrate can be modeled using the Drude approximation [6]:

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}\right) \quad \text{where} \quad \omega_p^2 = \frac{Nq^2}{\varepsilon_0 \varepsilon_\infty m^*}, \quad \Gamma = 1/\tau = \frac{q}{\mu m^*} \tag{1}$$

Here, ε_∞ is the high frequency dielectric constant, ω is the angular frequency. The plasma frequency ω_p and the relaxation frequency Γ (i.e. damping term) are obtained from the scattering time τ, the electron effective mass m*, the electron mobility μ, the electron charge q, and the electron density N (which is the same as the doping level N_D, assuming full ionization of dopants). Employing the dielectric constant and depletion width for each bias, we could perform electromagnetic simulations and obtain metamaterial transmission spectra. These simulations matched the experimentally observed red-shifts reasonably well.

The mid-IR spectral range is technologically important for a number of applications, including chemical/biological sensing, thermal imaging, and free-space optical communication. Thus, we expect that this electrical tuning of metamaterials can find novel applications in chip-scale active infrared devices.

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