Semiconductor approaches for tunable metamaterials in the mid-infrared

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Abstract

Planar metamaterials can be tailored to exhibit a wide variety of optical responses such as reflection and transmission notches and highly dispersive transmission. In addition, these metamaterials can exhibit strong near-field coupling to dipole transitions located in layers placed in close proximity to the metallic resonators. Semiconductor heterostructures allow great flexibility for engineering desired dipole transitions and also allow for tuning of the transitions through the application of an electrical bias. Thus, the combination of widely tailorable metamaterial properties along with the tunablity offered by semiconductor heterostructures can provide the foundation for a new class of electrically controlled photonic devices in the mid-infrared.

1. Introduction

Planar metamaterials (MM) (or "metafilms") offer a promising platform for new types of active optical devices. Resonances in these metamaterial structures can be scaled by geometry and their spectral response is exquisitely sensitive to the local dielectric environment which can be changed using a number of tunable dielectrics.[1-3] Arrays of metamaterial resonators have already been used as amplitude and phase modulators at terahertz frequencies.[4,5] In this paper we will describe two approaches to tailor the interactions between planar MMs and infrared transitions or "absorbers" in semiconductor heterostructures and discuss applications for electrical tuning of metamaterials.

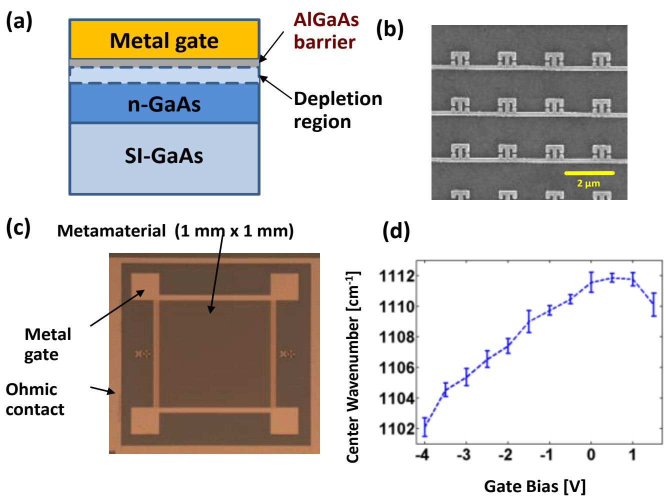

Fig. 1: (a) Schematic cross section of the device. The depletion region width is varied by applying an external voltage. (b) SEM image of the MM layer. The SRRs are connected by electrical bus lines. (c) Optical microscope image of the device. (d) Center frequency of the MM resonance as a function of gate bias.

2. Metamaterials coupled to highly doped layers

Recently, we demonstrated electrically tunable mid-IR MMs based on depletion-type semiconductor devices.[6] Split ring resonators (SRR) exhibiting a fundamental resonance in the mid-IR are electrically connected and serve as a metal gate. With a reverse bias applied to the metal gate, the refractive index of the substrate directly underneath the metallic resonators varies through changes in the depletion width in a highly doped semiconductor. This, in turn, causes a shift in the resonant frequency of the SRRs. Fig. 1 (a) shows a schematic cross section of the device structure and Figs. 1b and 1c show an SEM and optical micrograph of the SRR array. The experimentally measured shifts of the SRR resonant frequency are shown in Fig. 1(d). Further design guidelines and theory of these tunable metamaterials using these and other III-V semiconductors will be presented in the talk.

3. Metamaterials coupled to intersubband transitions (IST)

Another tuning mechanism that relies on coupling to electrically tunable optical transitions is the interaction of metamaterial resonances with intersubband transitions (IST) in semiconductor heterostructures[7] (see Fig. 2). An example of an electrically tunable transition designed for the mid-IR is shown in Fig. 3: two asymmetric coupled GaAs quantum wells, 5.7nm and 2.5nm wide, are separated by a 1 nm layer of $Al_{0.5}Ga_{0.5}As$ and sandwiched between two $Al_{0.5}Ga_{0.5}As$ layers. The energy levels of this coupled well design show a strong dependence on an applied electrical bias. The first three subbands and their wavefunctions (modulus) shown in this figure (for biases of 0 and -75 kV/cm) are determined using a self consistent solution of the Schrödinger and Poisson equations. A uniform distribution of dopants was assumed in the wider well. The 2D doping density was $N=8\times10^{11}$ cm^{-2}. As can be seen in Fig. 3(c), E2-E1 (and E3-E2) exhibit a strong dependence on bias and thus can be used as a “voltage tunable dielectric” to tune and manipulate the interaction with the MM resonators. The coupling of this quantum well structure to MM resonators with no external bias was observed experimentally and reported in Ref. 7.

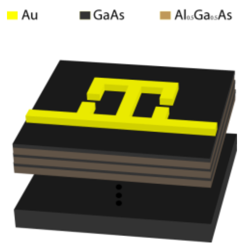

Fig. 2: Schematic cross section of a MM array fabricated on top of a quantum well heterostructure.

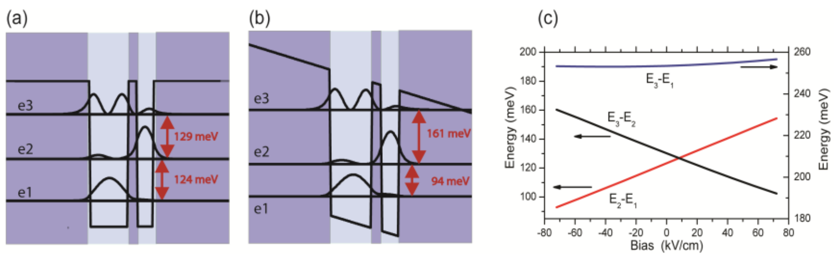

Fig. 3: (a) The potential energy (solid black lines) of two asymmetric coupled GaAs QWs with $Al_{0.5}Ga_{0.5}As$ barriers. (b) The potential energy with an applied a bias of -75 kV/cm. (c) The dependence of three lowest ISTs on the bias.

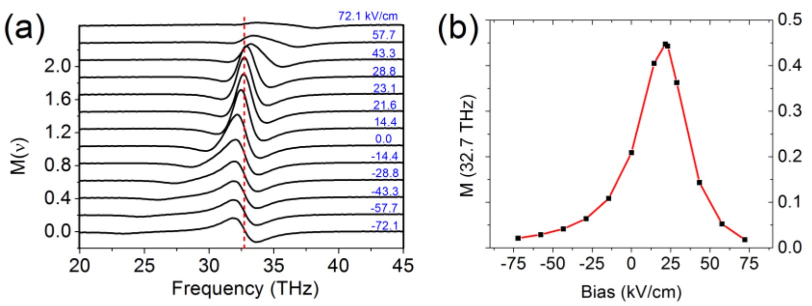

Fig. 4: (a) The modulation depth (as defined below) for several applied biases. A vertical offset was inserted between the spectra so that the y-axis labels refer only to the first spectrum. (b) The modulation depth at 32.7 THz as function of the applied bias. The data corresponds to the dashed red line in (a).

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The modulation depth, defined as $M(\nu) = (T_{QW}(\nu) - T_{ref}(\nu)) / T_{ref}(\nu)$, of a planar MM array coupled to these structures is shown in Fig. 4.[8] In this expression, $T_{QW}(\nu)$ ($T_{ref}(\nu)$) is the transmission through the QW (reference) sample at frequency ν. Fig. 4(a) shows $M(\nu)$ as a function of the frequency for different bias voltages. Note that the spectra are offset in the y- direction so the y-axis labels are correct only for the first spectrum (-72.1 kV/cm). Fig. 4(b) shows $M(\nu)$ for ν=32.7 THz (9.2 μm) as a function of the applied electric field. At this frequency, a peak modulation of 45% is observed at a bias of 23.1 kV/cm.

4. Conclusion

We have demonstrated that metamaterial resonators can be coupled to semiconductor heterostructure to form tunable photonic devices operating at infrared wavelengths. It is anticipated that the performance presented here can be improved by tailoring the near-field behavior of the metamaterial resonators to enhance the overlap with the quantum well transitions, as well as to satisfy selection rules for the quantum well transitions.

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