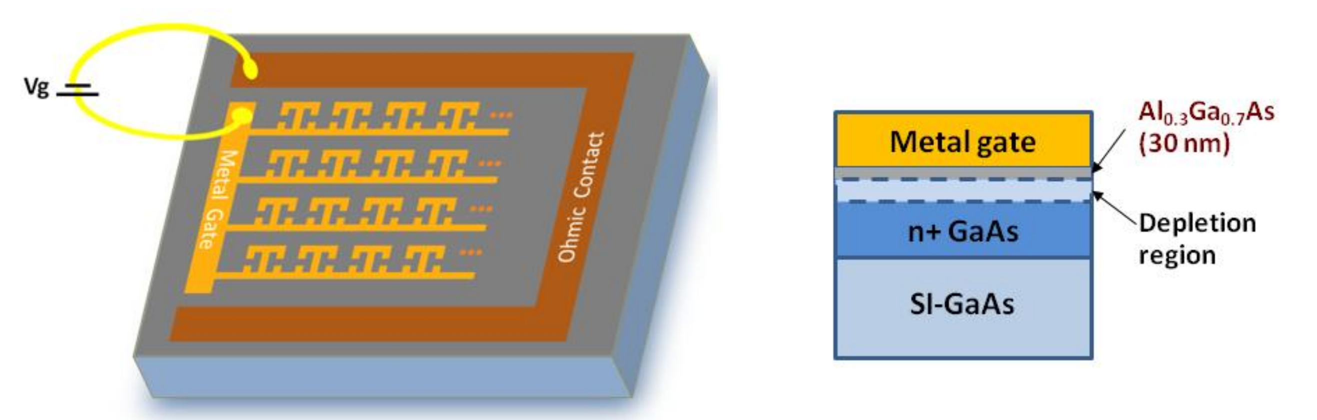
SAND2012-2235 C

Electrically Tunable Mid-Infrared Metamaterials based on Semiconductor Device Structures

Young Chul Jun[1,*], John Reno[1], Eric Shaner[2], and Igal Brener[1,2]

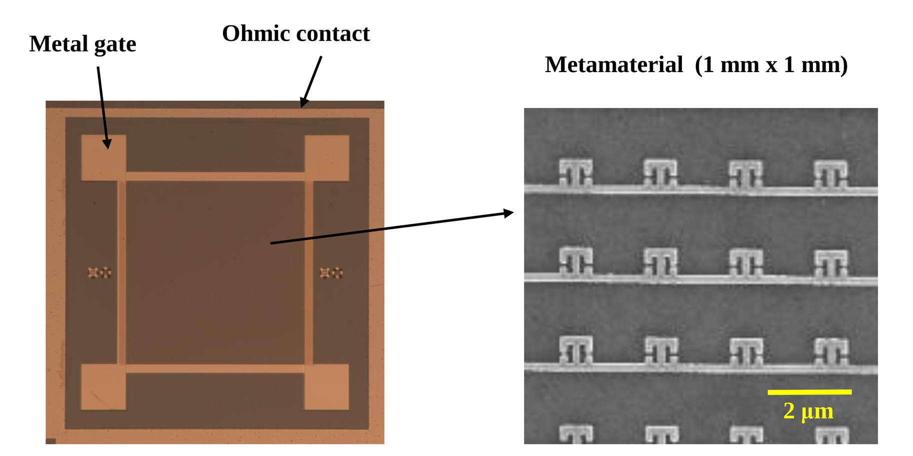
[1]Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories; [2]Sandia National Laboratories
** Email: youngchul.jun@sandia.gov*

Electrically Tunable IR Metamaterials

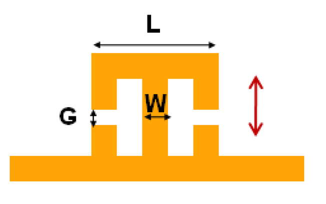


We demonstrate electrically-controlled active tuning of mid-infrared metamaterials based on depletion-type semiconductor devices. The depletion width in an n-doped (N_D = 5 x 10^{18} cm^{-3}) GaAs epilayer changes with the electric gate bias, inducing a change of the substrate permittivity and leading to frequency tuning of the metamaterial resonance. We present both theoretical analysis and experimental measurement of bias-dependent transmission spectra. We also discuss the possible ways to increase tunability further. This electrical tuning is generally applicable to a variety of infrared metamaterials and plasmonic structures, which can find novel applications in chip-scale infrared devices.

Device Fabrication



- Metal gate (Ti/Au) and ohmic contact (Ge/Au/Ni/Au) were defined by optical lithography
- A 1 mm by 1 mm metamaterial layer (i.e. SRR arrays) was fabricated by electron beam lithography and connected to the metal gate contact



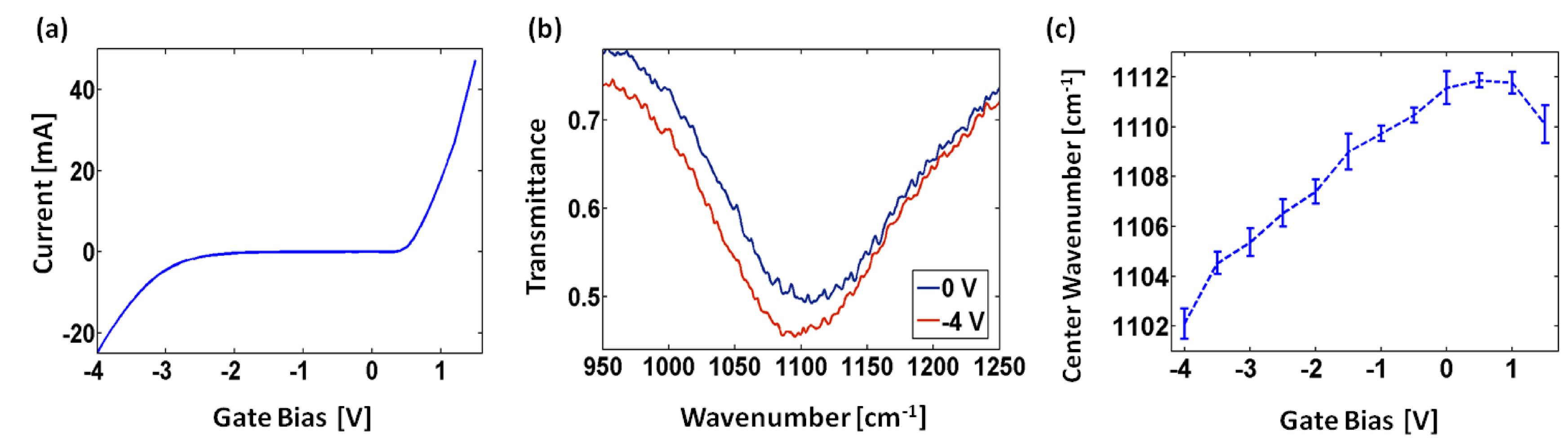
- Dimension of Gold Split Ring Resonator: L = 720 nm, W = 130 nm, G = 110 nm
- Thickness: Ti 5 nm / Au 60 nm
- Period between SRRs: 2 μm

FTIR Transmission Measurements

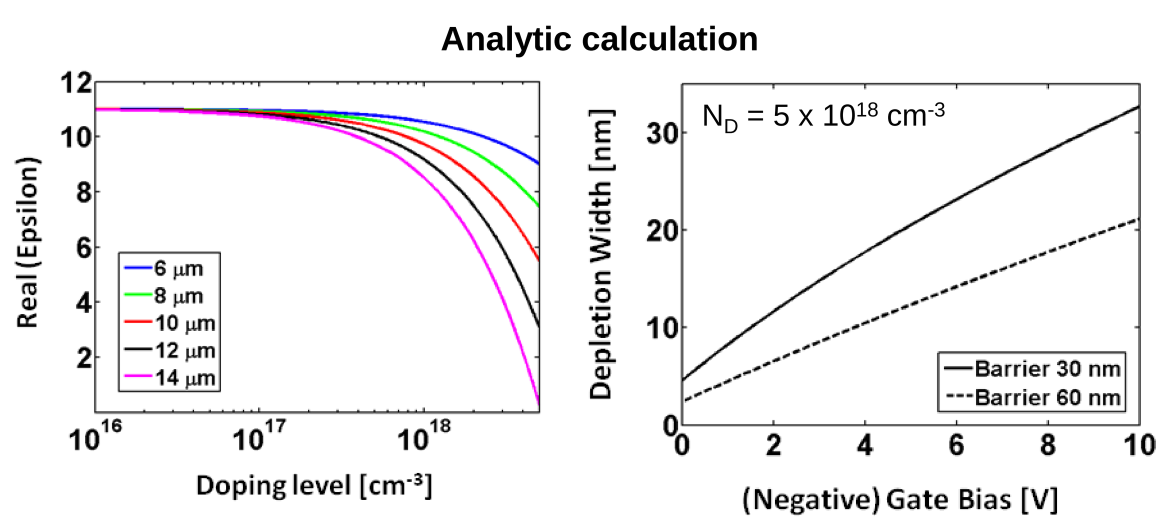
a) IV curve implies that the depletion region is formed at the metal-semiconductor junction and its width increases with a reverse bias

b) FTIR (Fourier-transform infrared spectrometer) transmission measurement at room temperature. The SRR resonance has a red-shift upon the application of a reverse bias. The shift is relatively small, but clearly observable.

c) The resonant frequency gradually red-shifts with a negative bias, as expected from a gradual depletion width change

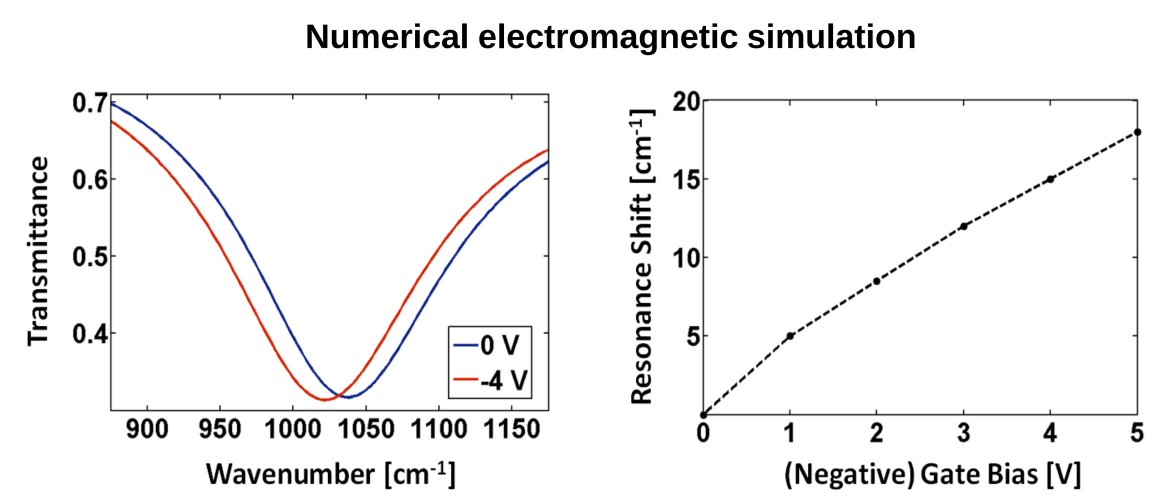


Theory of Device Operation



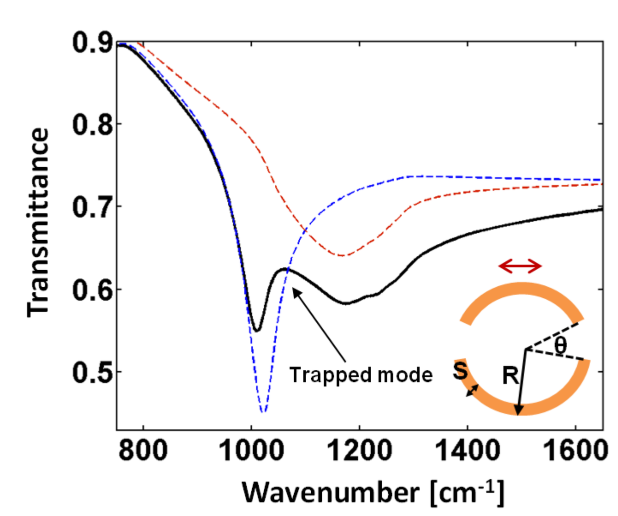
$$\varepsilon = \varepsilon_\infty \left[1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}\right] \quad \text{where} \quad \omega_p^2 = \frac{Nq^2}{\varepsilon_\infty \varepsilon_0 m^*} \quad \& \quad \Gamma = 1/\tau = \frac{q}{\mu m^*}$$

$$W_{depletion} = \left[\frac{2\varepsilon_{GaAs}\varepsilon_0}{qN_D}(-\phi_s)\right]^{1/2} \quad \text{where} \quad Vg = \phi_s - \frac{\varepsilon_{GaAs}}{\varepsilon_{AlGaAs}} W_{barrier} \left[\frac{2qN_D}{\varepsilon_{GaAs}\varepsilon_0}|\phi_s|\right]^{1/2} + \phi_{MS}$$



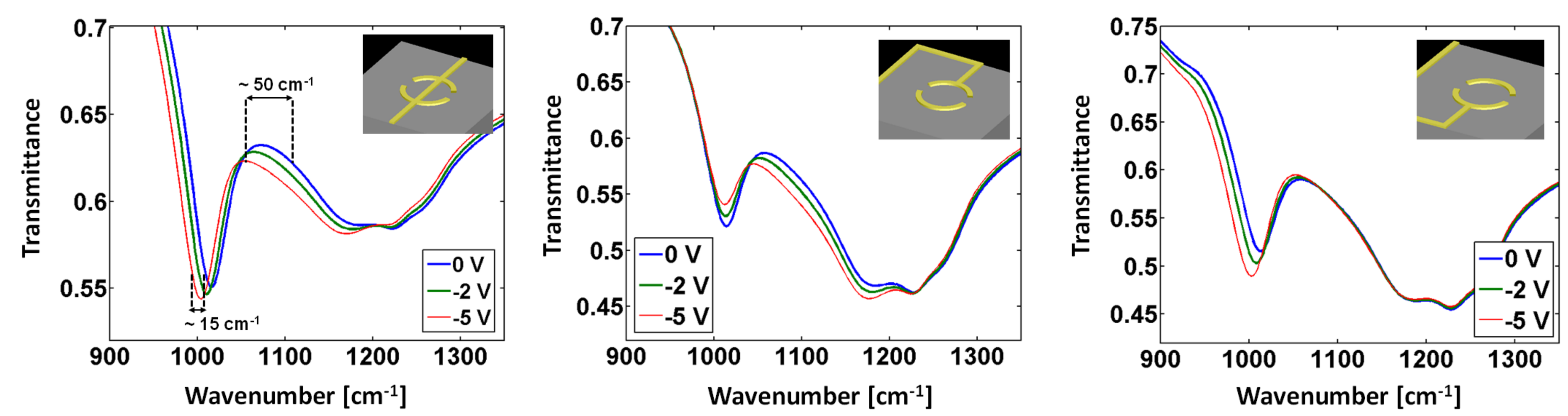
- Analytic calculation of ε and $W_{depletion}$
  - Drude model calculation of dielectric constants in n-GaAs
  - Dielectric constant reduces rapidly in a high doping region
  - Depletion width calculation using MIS (metal-insulator-semiconductor) formula
  - Depletion width gradually increases with a negative bias
- Numerical electromagnetic simulation of SRR transmission
  - Estimate the resonance shifts with numerical simulations (FDTD), employing analytically calculated ε and $W_{depletion}$
  - A broadband light pulse was incident from top and polarized normal to the SRR gap to excite a LC resonance
  - The transmission dip exhibits gradual red-shifts with a bias
  - This can be understood from a LC resonator model. When the depletion width increases, the substrate refractive index increases and the resonance red-shifts
- Electrical tunability can be further increased either by improving:
  - Metamaterial part - e.g. optimizing field overlap with the depletion layer or having narrower resonance peaks
  - Semiconductor part - e.g. using semiconductors which have a smaller electron effective mass and larger dielectric constant change. For instance, InSb has much smaller electron effective mass than GaAs: $m_{InSb}^* = 0.014 m_0$, $m_{GaAs}^* = 0.067 m_0$.

Asymmetric Metamaterial Designs



- Two metal arcs have resonances at slightly different frequencies
- Transparency window appears within a narrow frequency range due to the destructive interference from two resonator arms
- The trapped mode is caused by interference, so it can be more sensitive to a substrate index change
- Metamaterial Dimension: R = 770 nm, S = 150 nm, θ = 35°, Period: 4 μm

- Different electric biasing schemes: both arms are biased or one single arm is biased
- We see different behaviors depending on the biasing scheme:



This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.