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Electrically-Controlled Thermal Infrared Metamaterial Devices

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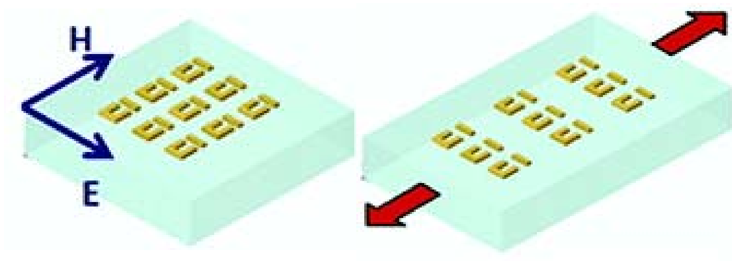
Sandia National Laboratories

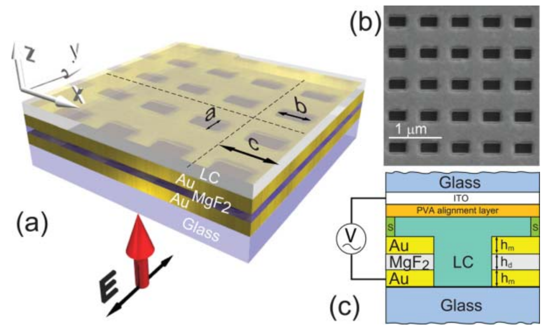
Tunable Metamaterials

Mechanical movement or stretching



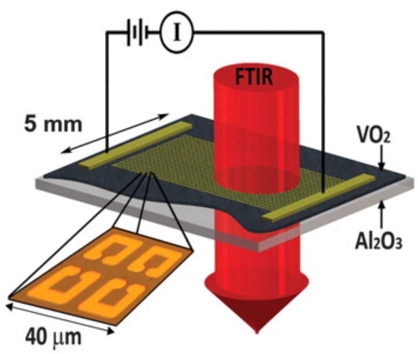
I. M. Pryce, Nano Lett (2010)

Re-orientation of liquid crystals



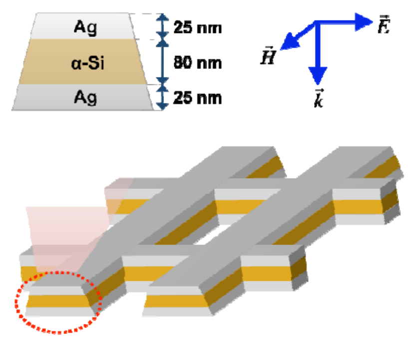
A. Minovich, APL (2012)

Phase transitions in VO_2



T. Driscoll, Science (2009)

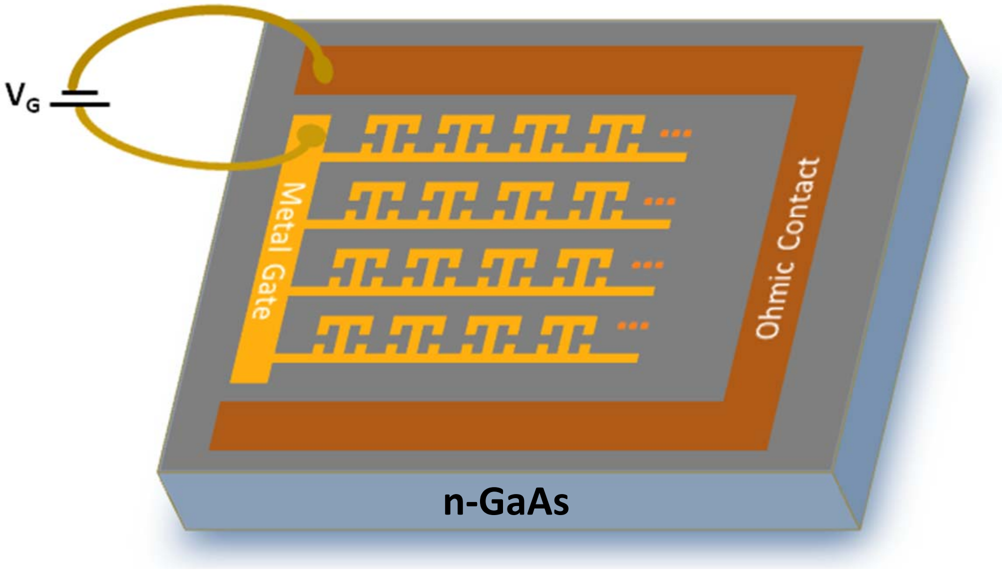
Optical free carrier generation

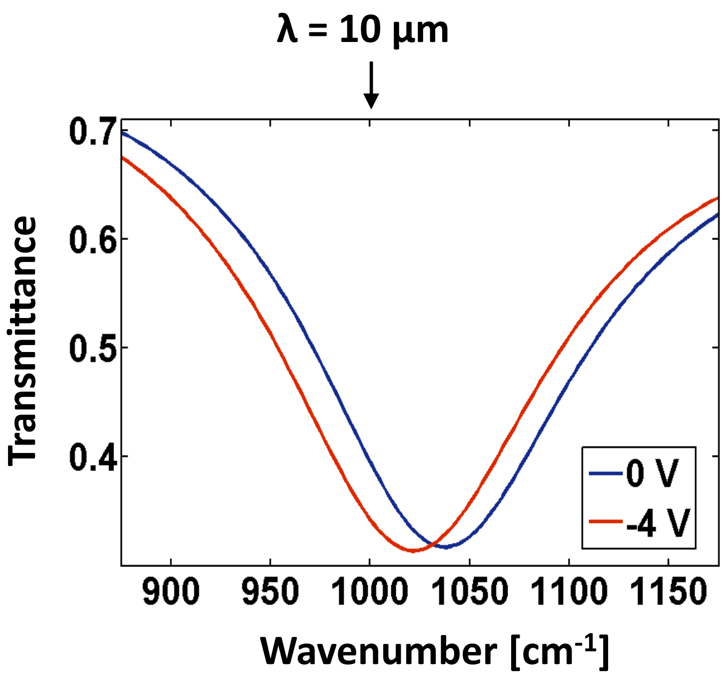


D.J. Cho, Opt. Express (2009)

- Electrical tuning based on semiconductor device structures is more technologically appealing for practical, chip-scale applications

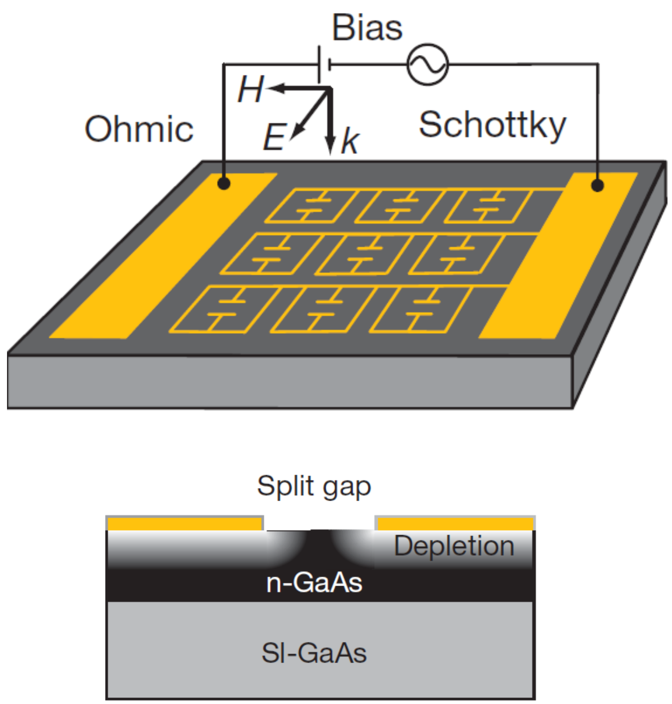
This talk: Electrically tunable mid-IR metamaterials



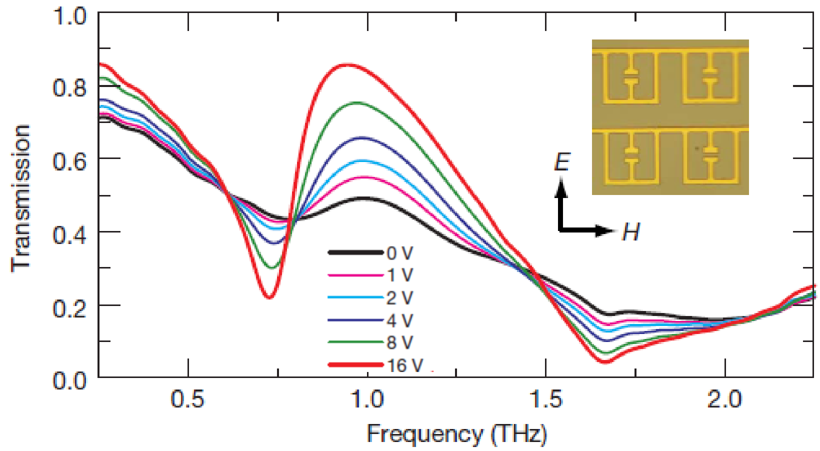


- Mid-IR frequency is important for sensing, thermal imaging, etc
- Planar metamaterial layer works as a metal gate too
- Depletion width in the doped layer changes with a gate bias
- Change of the substrate refractive index, Frequency tuning

Active THz Metamaterials

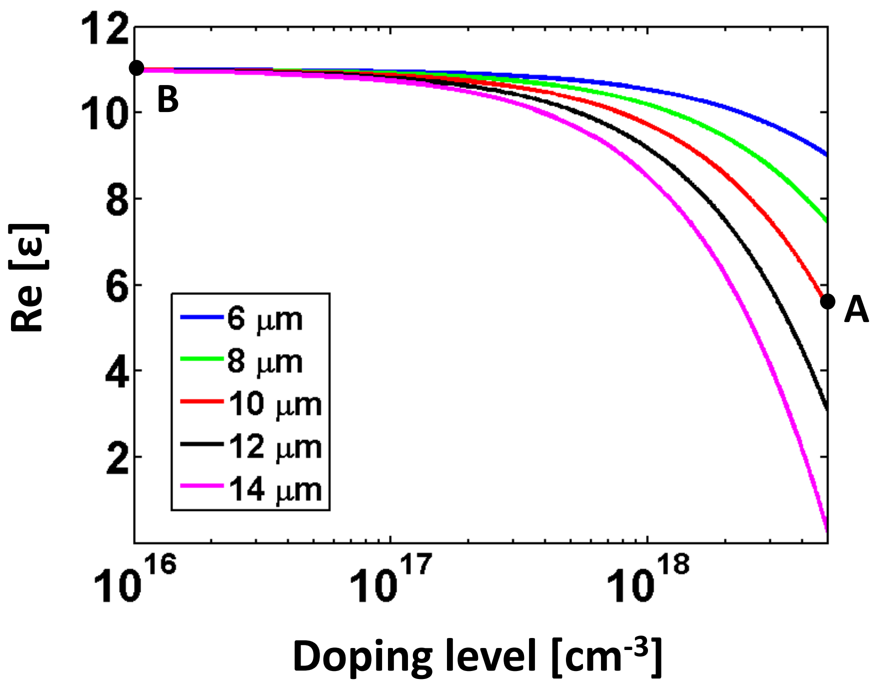


H. Chen, Nature 444, 597 (2006)
(Los Alamos National Labs)



- Electrical control of free carrier absorption
- Strong *amplitude modulation* at THz (~ 50 %)
- Free carrier absorption is much smaller at higher frequencies (such as mid-IR)

Dielectric constant of n-GaAs



*** Drude model :**

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \right)$$

Where the plasma frequency:

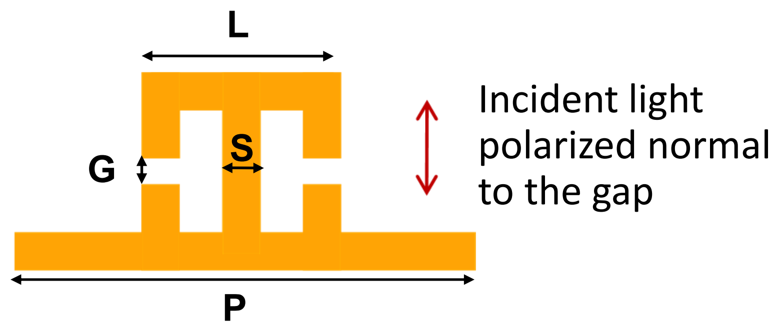
$$\omega_p^2 = \frac{Nq^2}{\varepsilon_0 \varepsilon_\infty m^*}$$

- Need a highly doped semiconductor layer
- Remove carriers by an external bias
- Induce a large dielectric constant change:

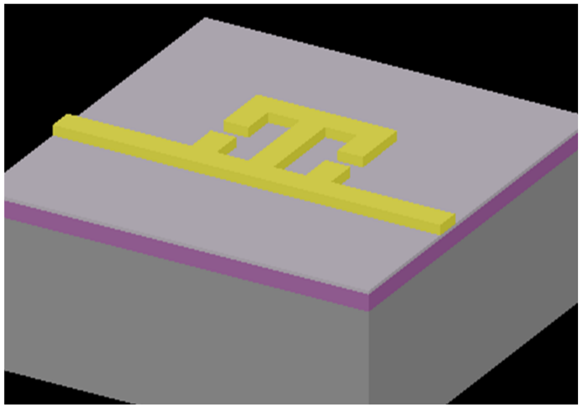
  e.g. $\Delta\varepsilon \sim 5.5$ for $\Delta N_D = 5 \times 10^{18}$ cm^{-3}, $\lambda_0 = 10$ μm (1000 cm^{-1})

Numerical Simulation of metamaterial transmission

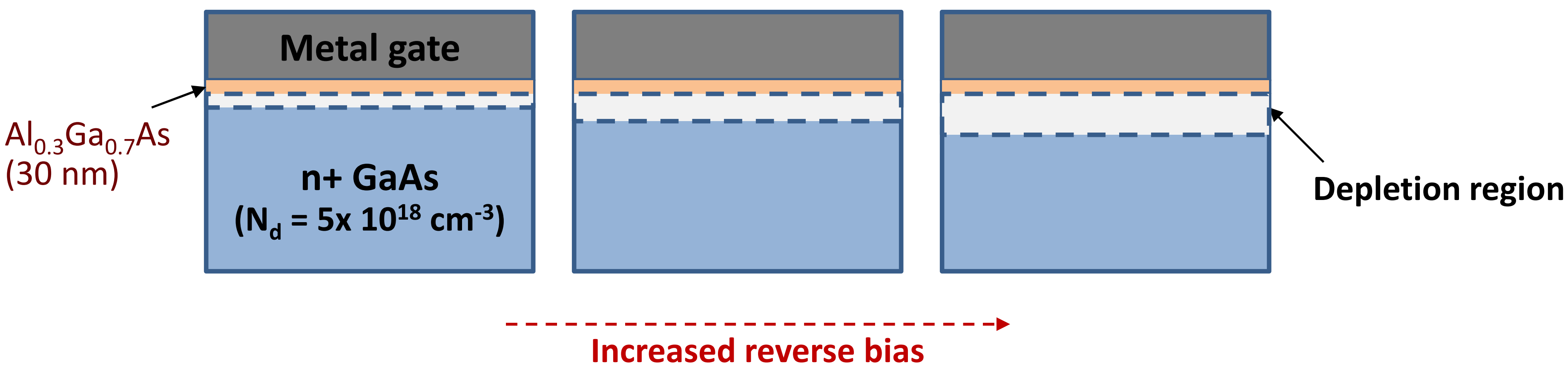
Modified split ring resonators (SRR) with an electrical bus line



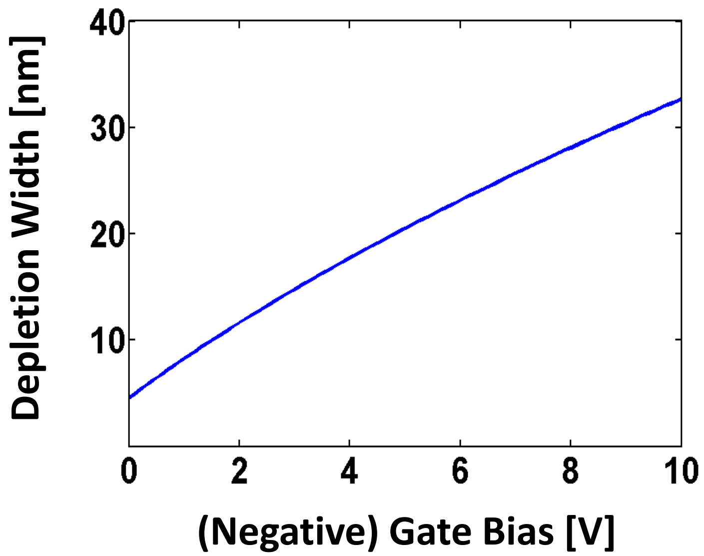
FDTD simulation domain



(L = 720 nm, S = 130 nm, G = 110 nm, P = 2 μm)



Numerical Simulation of metamaterial transmission

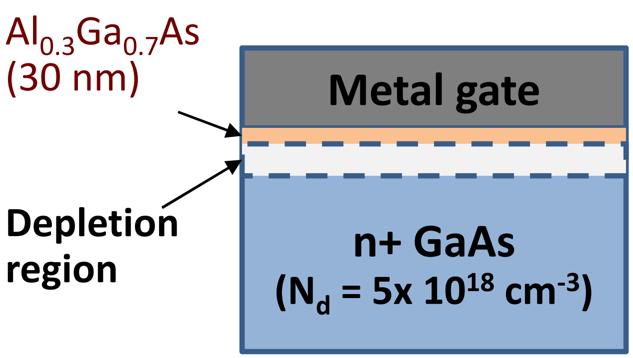


*** Depletion width for a MIS capacitor:**

$$W_{depletion} = \left[\frac{2\varepsilon_{GaAs}\varepsilon_0}{qN_D}(-\phi_s) \right]^{1/2}$$

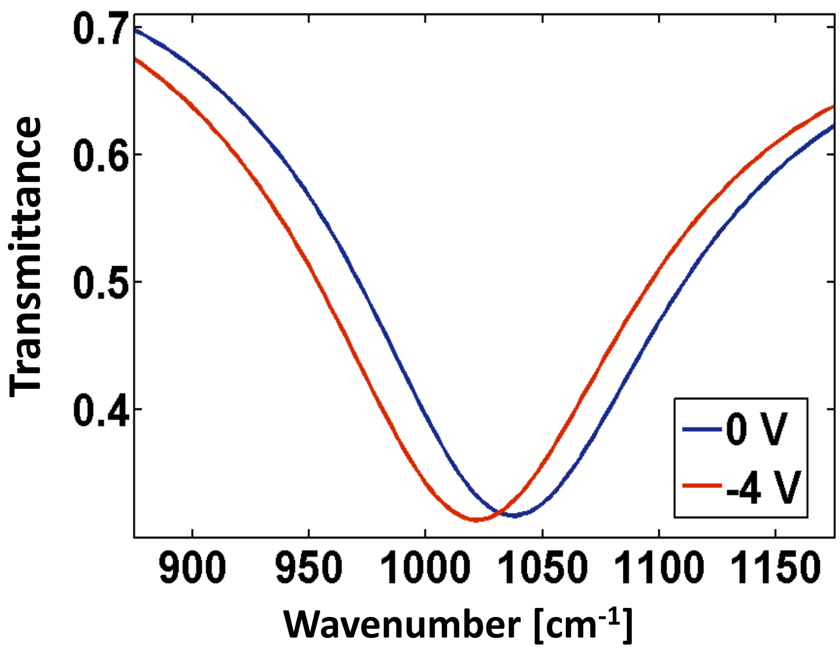
Where ϕ_s is a surface potential :

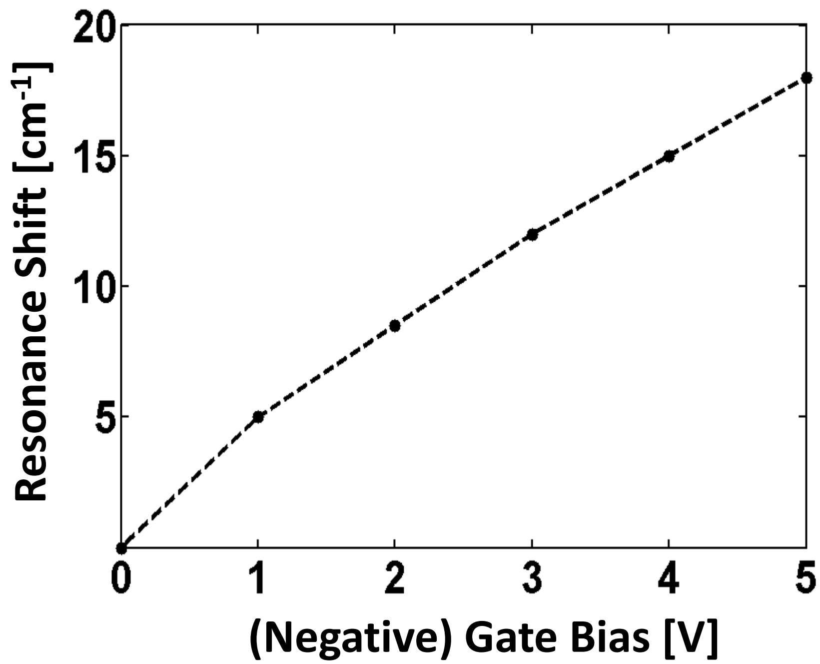
$$V_G = \phi_s - \frac{\varepsilon_{GaAs}}{\varepsilon_{AlGaAs}} W_{barrier} \left[\frac{2qN_D}{\varepsilon_{GaAs}\varepsilon_0} |\phi_s| \right]^{1/2} + \phi_{MS}$$



- Employ a different depletion width for each gate bias
- Repeat FDTD simulations

Numerical Simulations of metamaterial transmission

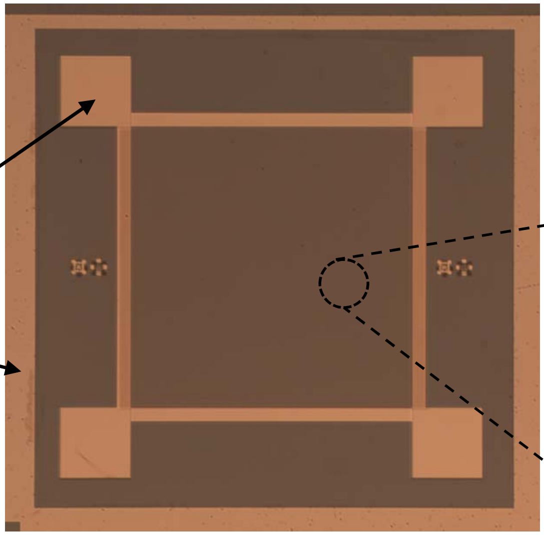




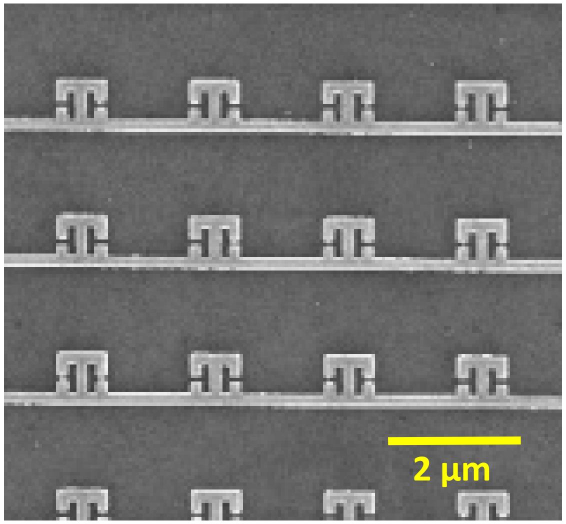
- FDTD simulation of SRR transmission
- Metamaterial resonance gradually red-shifts with a negative bias
- Tuning is relatively small, but still large enough to be observable clearly

Device fabrication: metal contacts + SRR array

Metal contacts patterned by Optical lithography



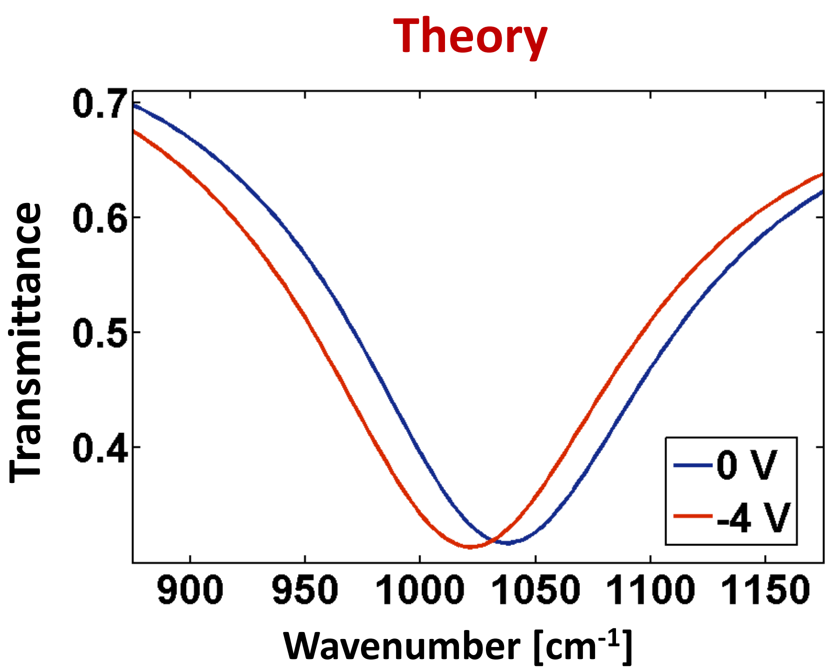
Metamaterial (1 mm x 1 mm)

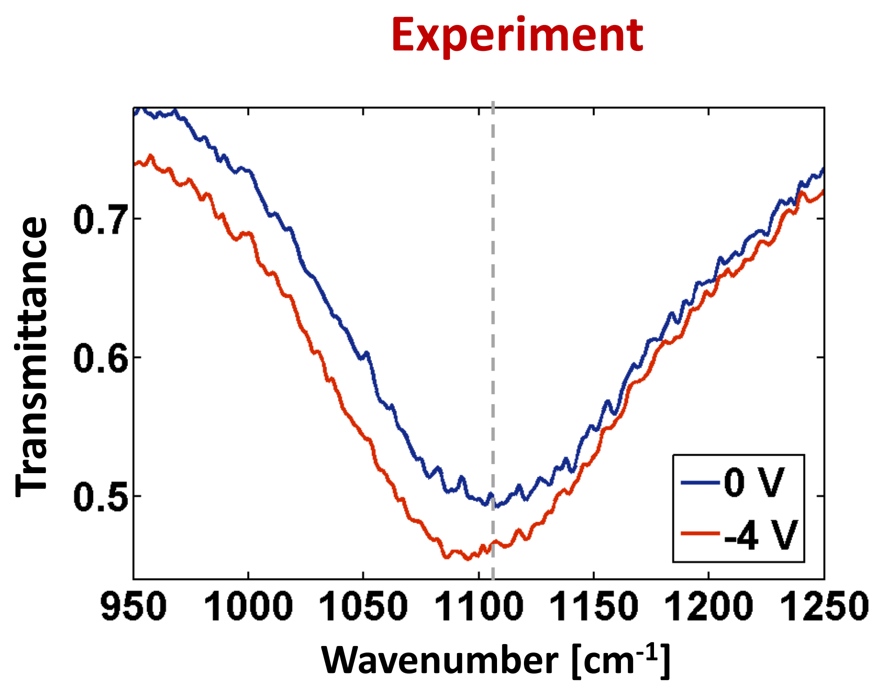


Gold SRR array patterned by Ebeam lithography (Connected to metal gate)

FTIR Measurements with an electric bias

Y. C. Jun et al, Opt. Express 20, 1903 (2012)

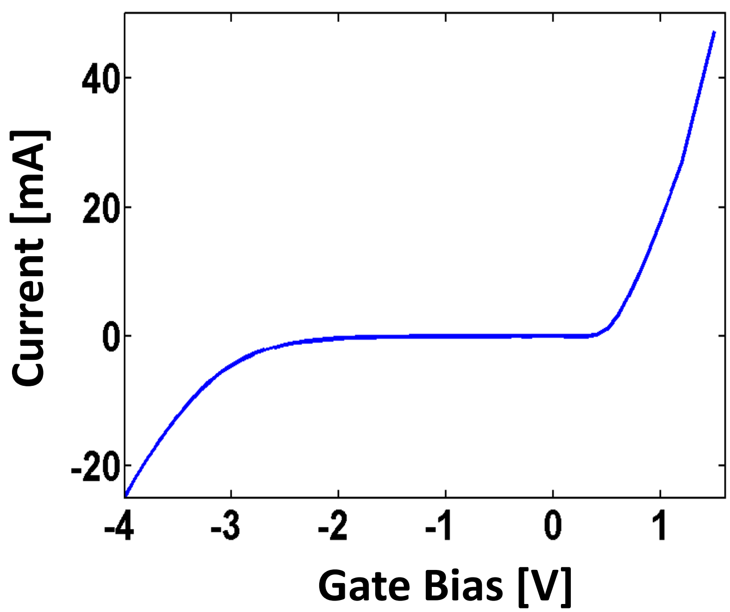


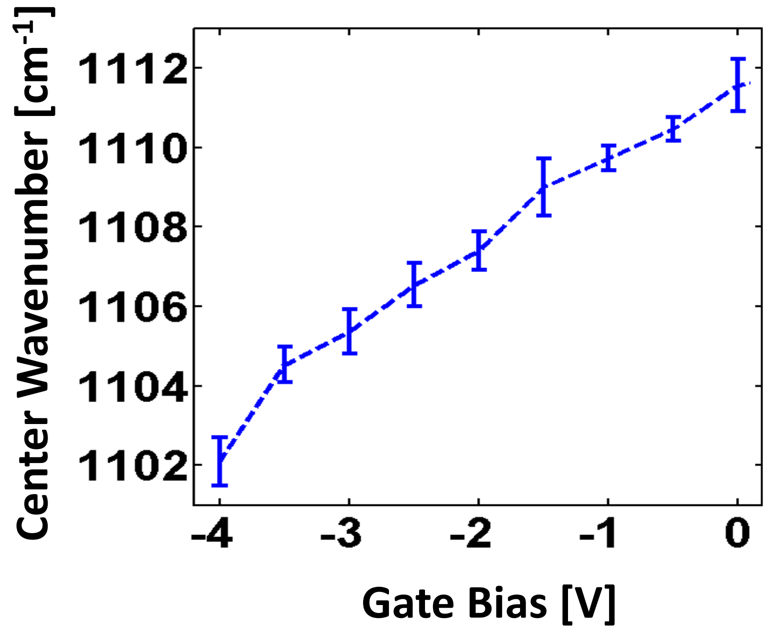


- FTIR transmission measurement at room temperature
- Metamaterial transmission spectrum changes with a bias
- Red-shift observed with a reverse bias, as expected

FTIR Measurements with an electric bias

Y. C. Jun et al, Opt. Express 20, 1903 (2012)





- Diode-like IV characteristic
- Resonance gradually shifts with a bias

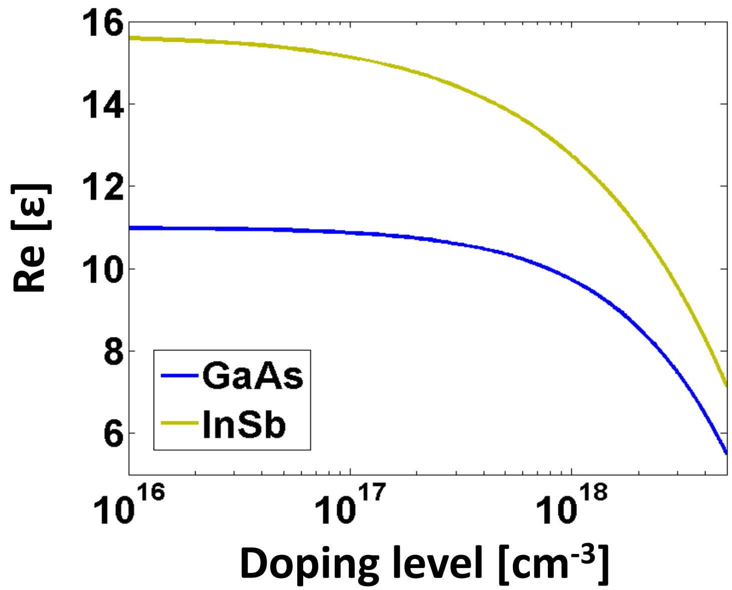
Tunability can be further increased

- Improving the semiconductor part

  e.g. smaller electron effective mass: $m_{InSb}^* = 0.014\ m_0$, $m_{GaAs}^* = 0.067\ m_0$

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \right)$$

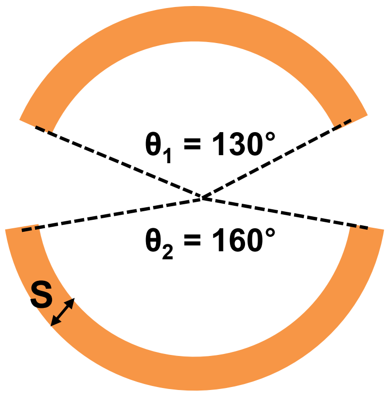
where $\omega_p^2 = \dfrac{Nq^2}{\varepsilon_0 \varepsilon_\infty m^*}$



- Improving the metamaterial part
  - better field overlap with the depletion region
  - narrower resonance

Asymmetric metamaterial design: Coupled resonators

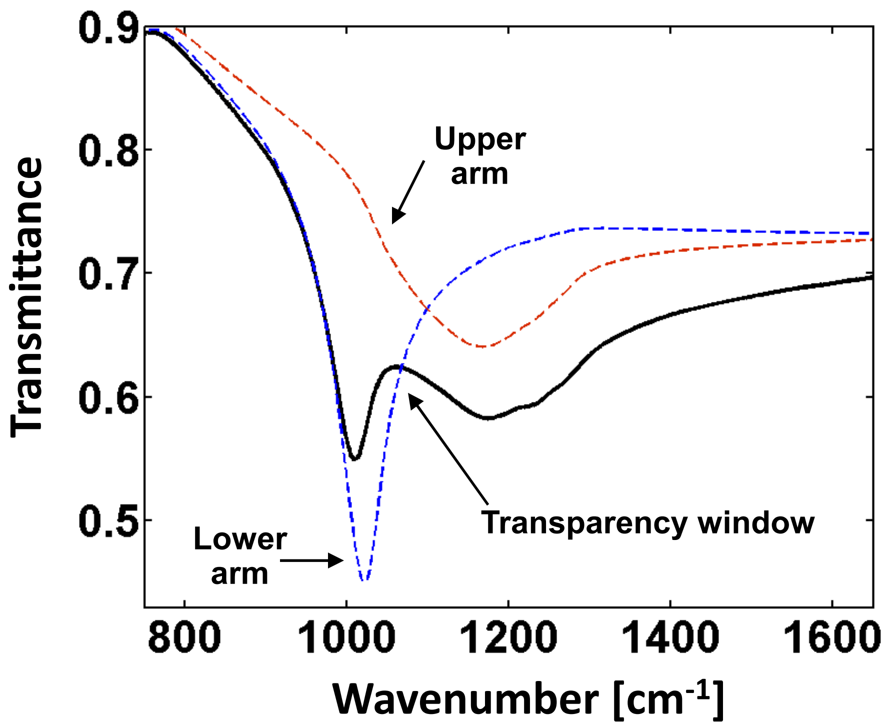
Classical analog of EIT
(N. Zheludev group)



(Radius = 770 nm, S = 150 nm)

Incident light polarized

Numerical simulation

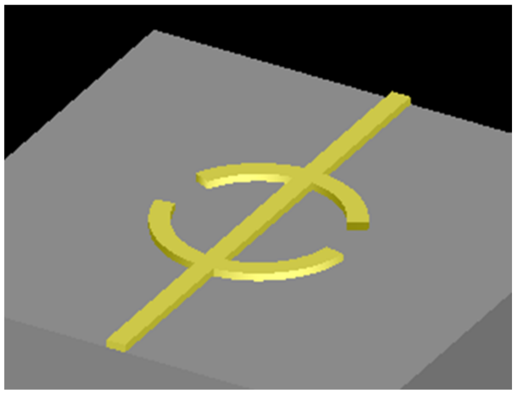


- Scale-down structure which is resonant at mid-IR
- Transparency window by the destructive interference of two resonances
- Interference part can be more sensitive to refractive index change

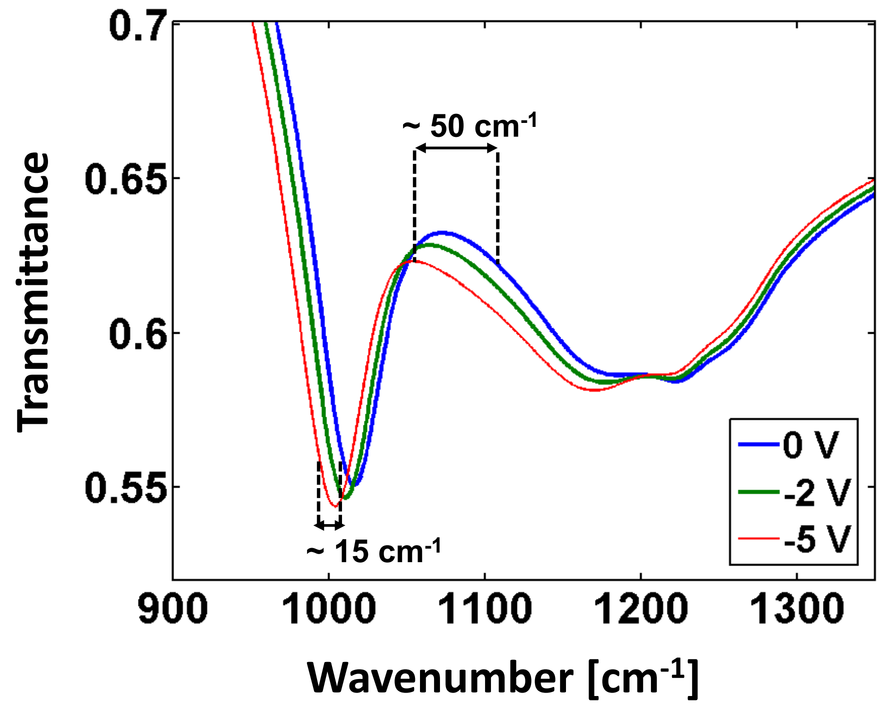
Asymmetric metamaterial design: Coupled resonators

Y. C. Jun et al, *submitted* (2012)

FDTD simulation domain



(Both arms are connected to the electrical bus line)

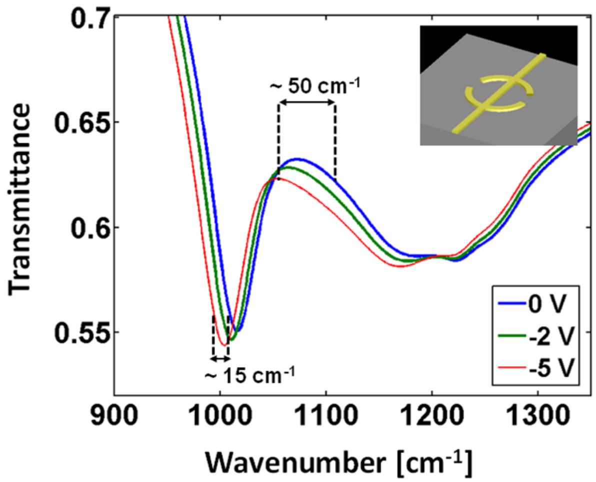


- Performed numerical simulations for different gate biases
- Interference part has a larger spectral change

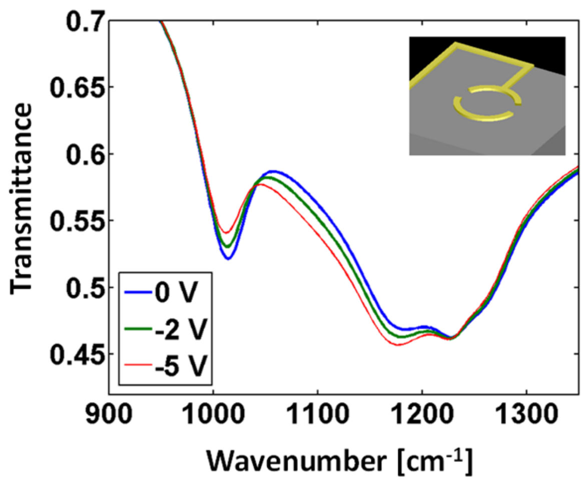
Asymmetric metamaterial design: Coupled resonators

Y. C. Jun et al, *submitted* (2012)

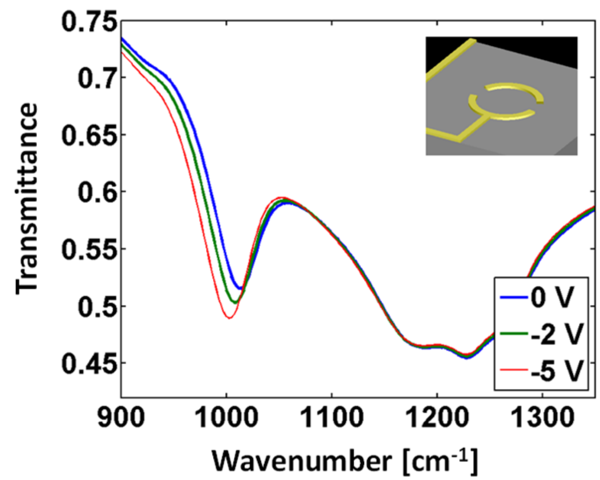
Numerical simulation



(Both arms are connected to the electrical bus line)



(Only Upper arm is connected to the electrical bus line)

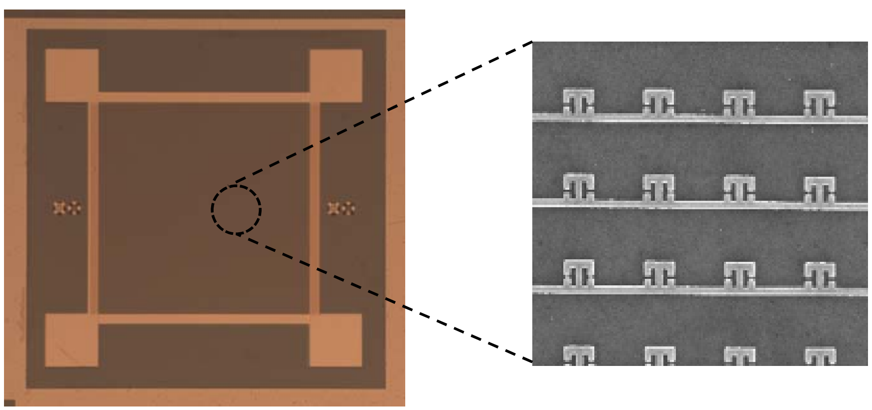


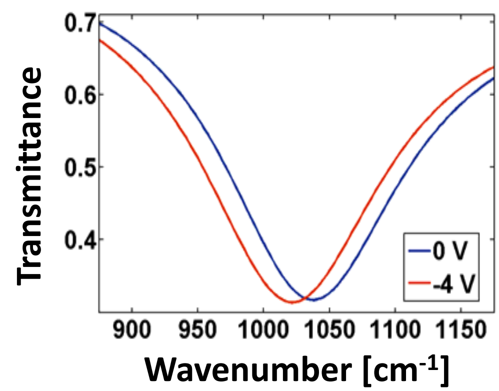
(Only Lower arm is connected to the electrical bus line)

- Depletion-type devices are good for local refractive index control
- We can electrically address each resonator arm separately
- Different biasing scheme produces different spectral changes

Conclusions

- Metamaterial layer was combined with semiconductor device structures
- Theoretical analysis and experimental data were presented
- The observed gradual red-shift with a bias was attributed to the refractive index change in the substrate
- Possible further improvements were considered
- This active tuning will be useful for various on-chip IR device applications





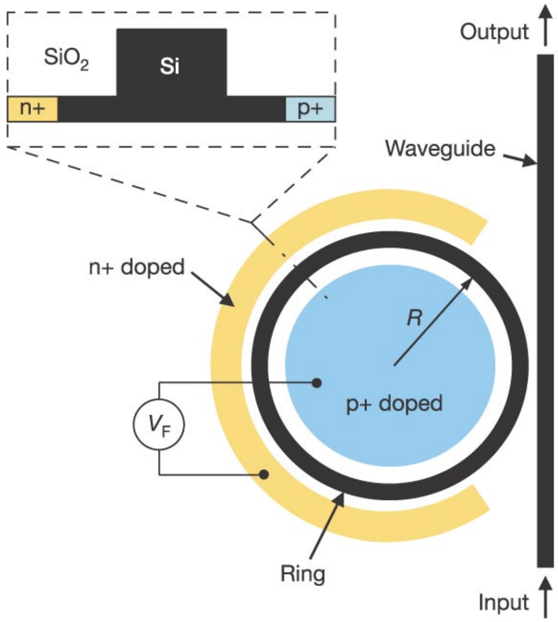
Thanks for your attention ..

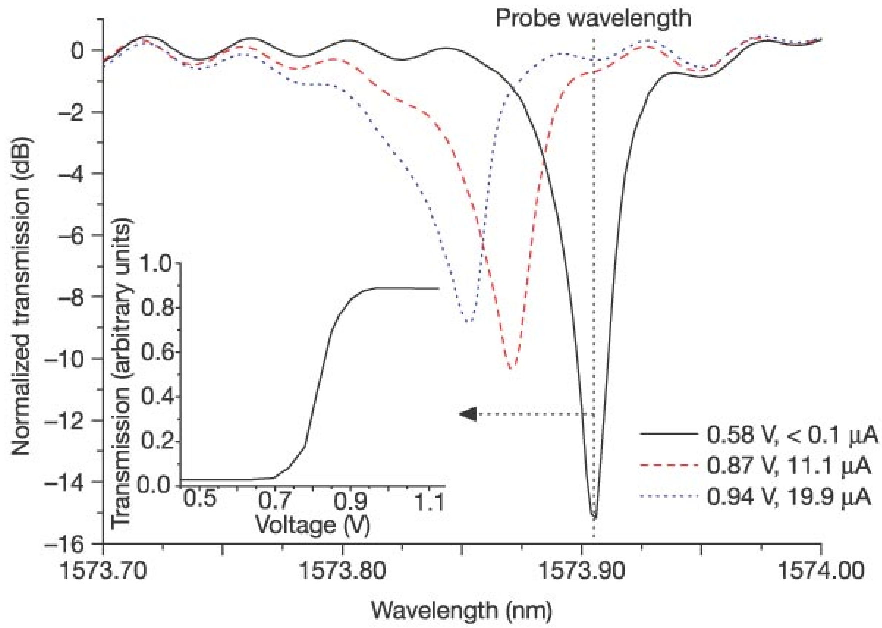
Electrical carrier injection or depletion in Photonics

Q. Xu, Nature 435, 325 (2005)

A. Liu, Nature 427, 615 (2004)

Si electro-optic modulators

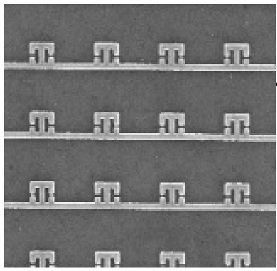


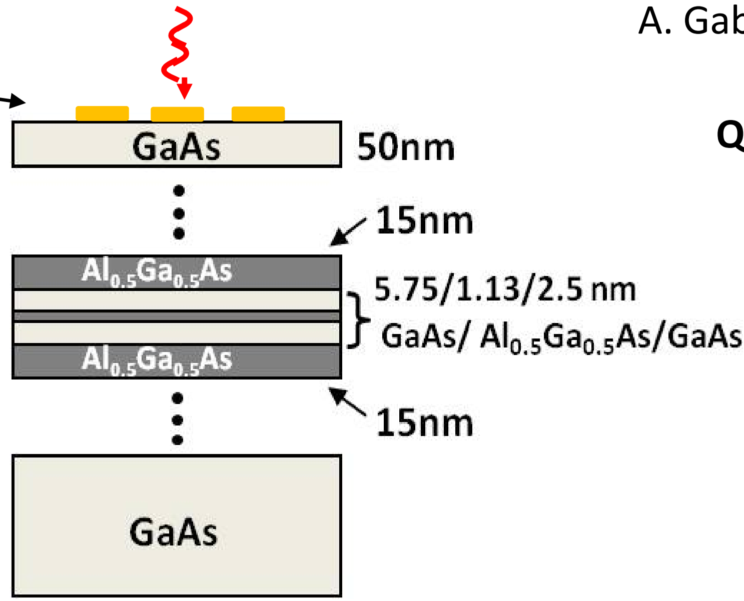


- Optical resonance control with carrier injection or depletion has been used in photonics (e.g. Si electro-optic modulators)

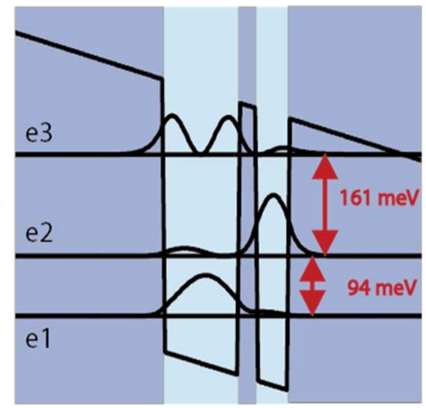
Other tuning mechanism for Active IR metamaterials

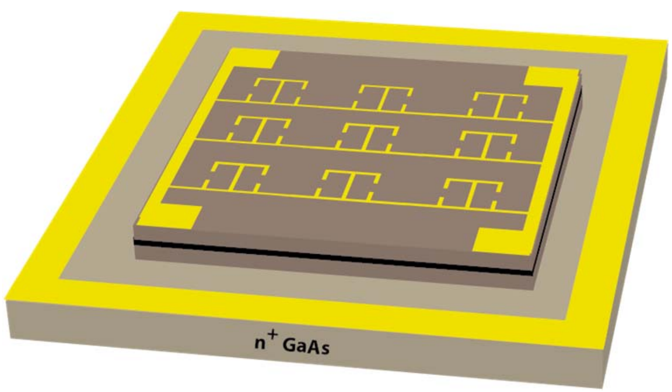
A. Gabbay et al, APL 98, 203103 (2011)
A. Gabbay et al, Opt. Express 20, 6584 (2012)

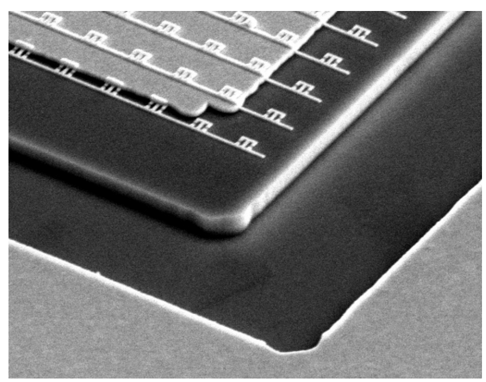




Quantum Well Intersubband transition







Device fabrication and characterization are ongoing ..