Semiconductor Epsilon-Near-Zero Nano-Optics

cint.lanl.gov

Young Chul Jun[1,*], John Reno[2], Luk Ting Shan[2,3], and Igal Brener[2,3]

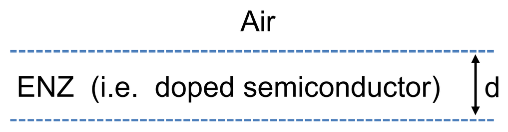
[1]Department of Physics, Inha University, Incheon 402-751, Republic of Korea
[2]Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories, Albuquerque, NM 87185, United States
[3]Sandia National Laboratories, Albuquerque, NM 87185, United States
* Email: youngchul.jun@inha.ac.kr

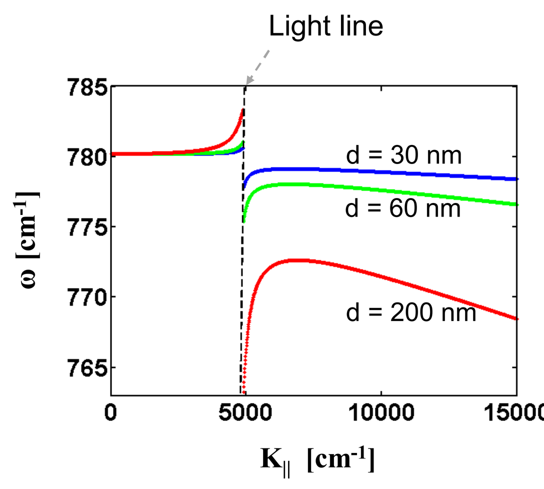
Epsilon-Near-Zero Strong Coupling

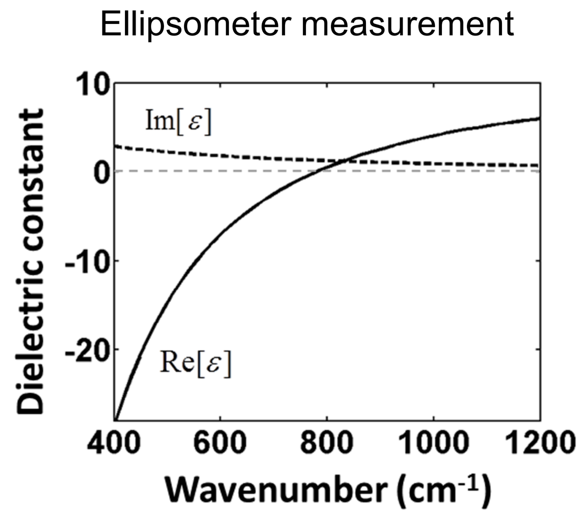
Dispersion relation of the TM mode in a 3-layer

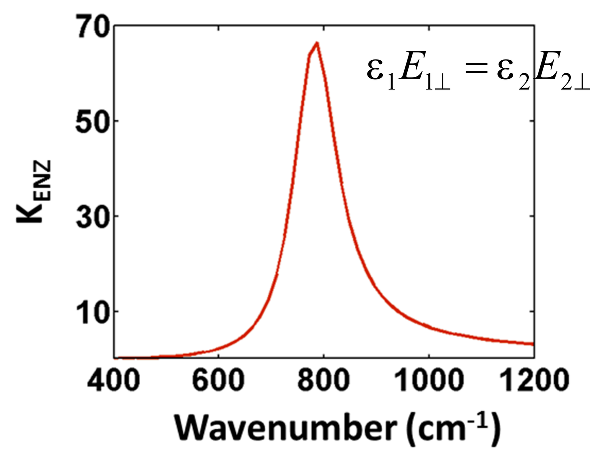
$$\left(1+\frac{\epsilon_1 k_{z,1}}{\epsilon_3 k_{z,3}}\right) = i\tan(k_{z,2}d)\left(\frac{\epsilon_2 k_{z,3}}{\epsilon_3 k_{z,2}}+\frac{\epsilon_1 k_{z,2}}{\epsilon_2 k_{z,1}}\right)$$

Numerical solution in complex domain (assuming complex freq, real K)

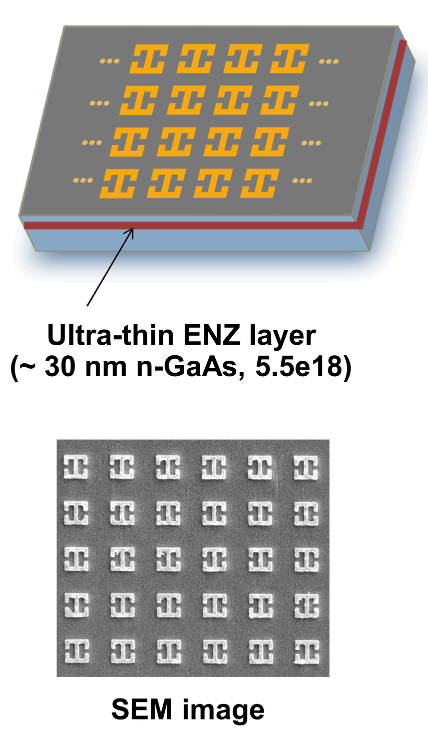


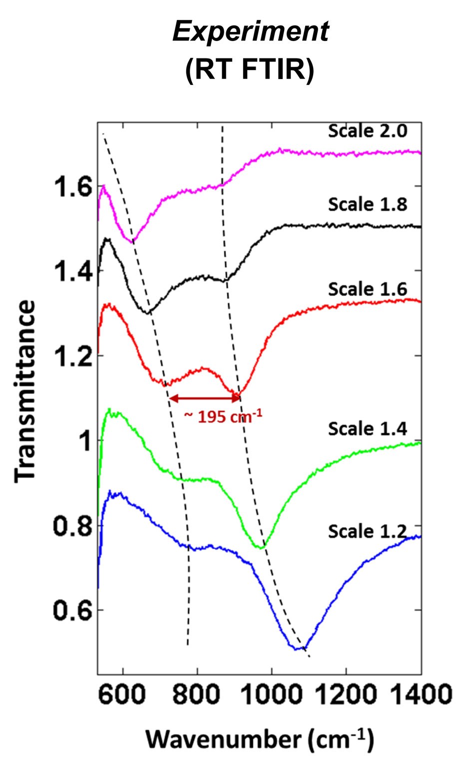


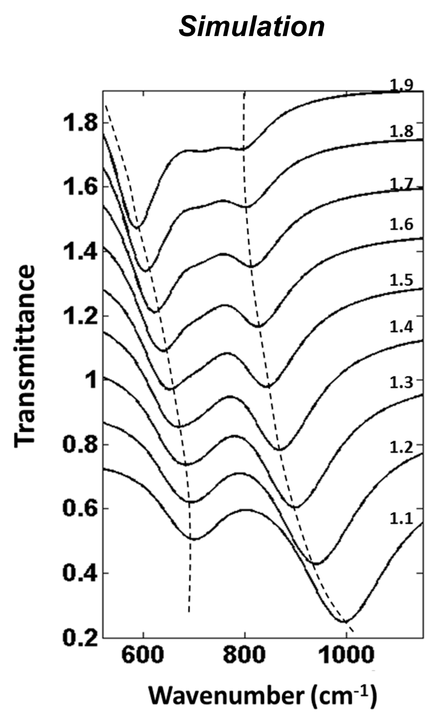


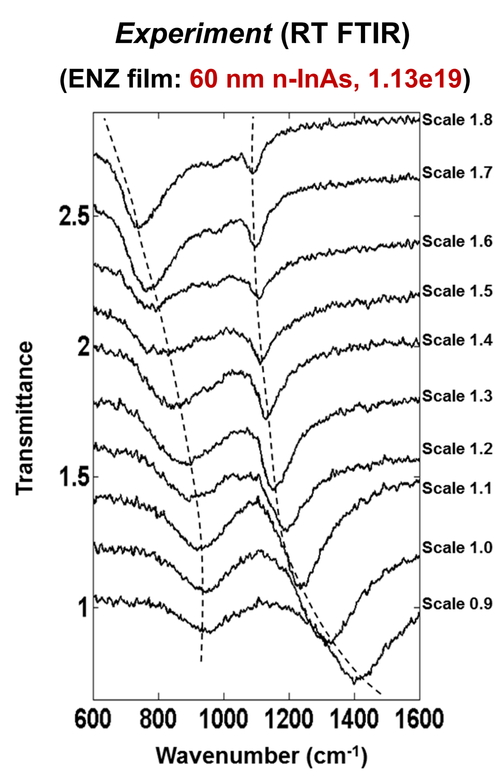


- Berreman mode (leaky mode), ENZ mode (bound mode)
- SRR provides near-field components with vary large $K_{||}$
- Ellipsometer measurement of n+ GaAs (5.5×10^{18} cm^{-3}) epilayer
- Large field enhancement in n+ GaAs can be obtained when Re[ε] ≈ 0 (780 cm^{-1})
- At the n-GaAs / GaAs Interface: $K_{ENZ} = |E_{ENZ}/E_{GaAs}|^2 = |\varepsilon_{GaAs}/\varepsilon_{ENZ}|^2$







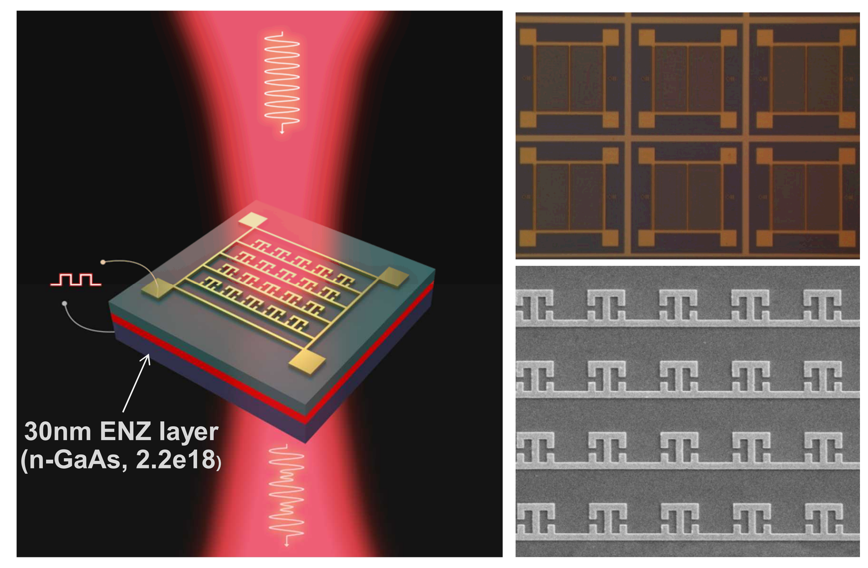


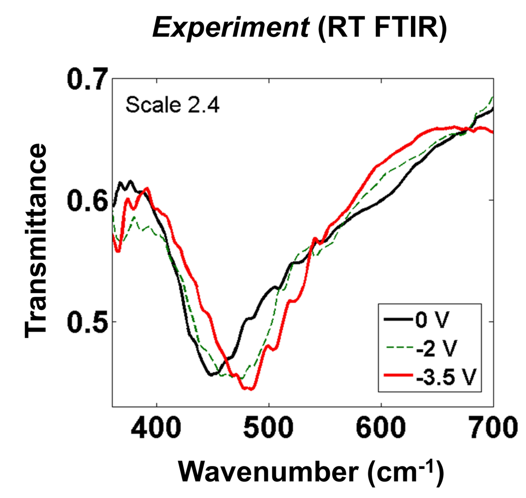
Y. C. Jun et al, *Nano Letters 13, 5391* (2013)

- Novel strong coupling between Metamaterial and ENZ mode
- Highly tunable optical strong coupling

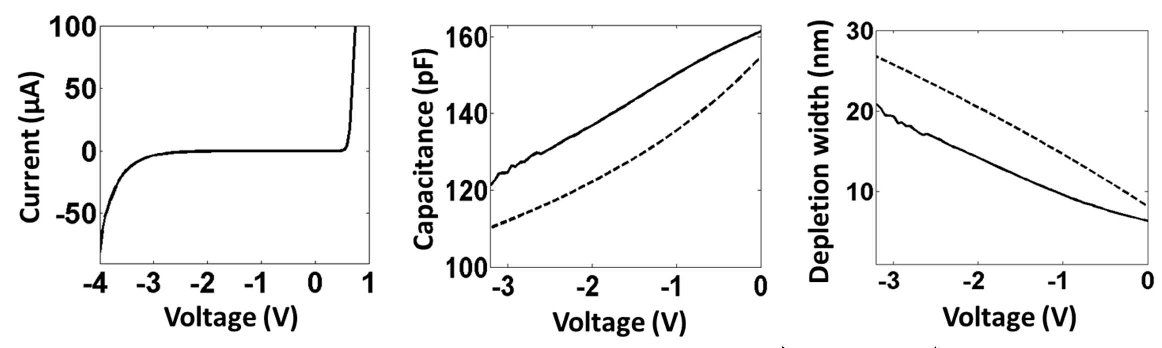
Electrically Tunable Strong Coupling

Y. C. Jun et al, *Nano Letters 13, 5391* (2013)

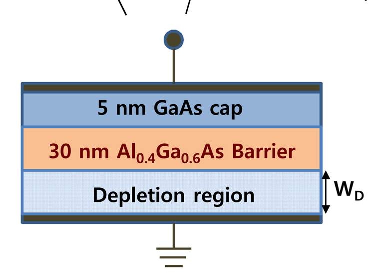




- Deplete the doped ENZ layer (i.e. reduce ENZ layer thickness)
- Electrically control coupling between MM resonance and ENZ modes
- Previous studies: using permittivity change in a thick doped substrate
  - Y. C. Jun et al, Opt. Express 20, 1903 (2012)
  - Y. C. Jun et al, J. Opt. 14, 114013(2012)

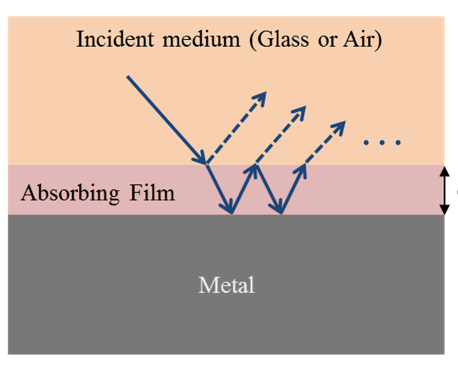


- IV, CV measurement with a test contact device (250 μm x 250 μ m in size)
- Leakage current is very small
- Depletion width gradually increases



Perfect Absorption in Ultra-thin Films

T. S. Luk, Y. C. Jun et al, *submitted*



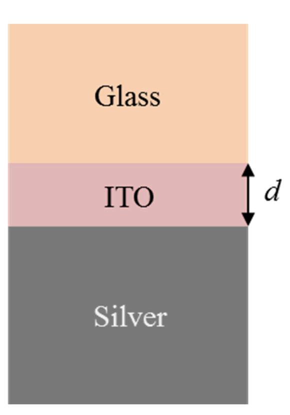
$$r = \frac{r_{01}+r_{12}e^{2i\theta}}{1+r_{01}r_{12}e^{2i\theta}}$$ (Airy's formula)

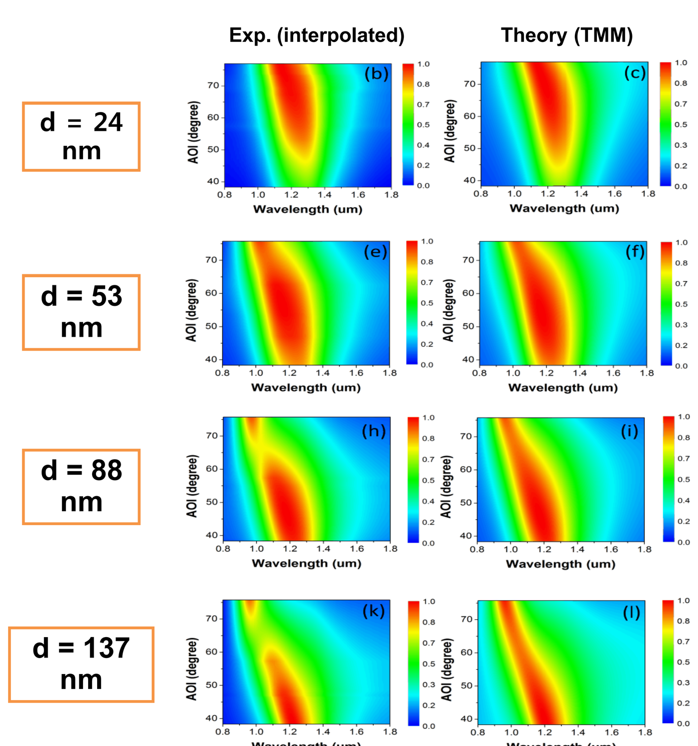
$$r_{01}+r_{12}e^{2i\theta}=0$$

$$\frac{2\pi d_{PA}}{\lambda_{PA}} = \frac{\varepsilon_1''}{n_0^3\tan(\theta_{PA})\sin(\theta_{PA})}$$

(when Re[ε] → 0, i.e. Epsilon-Near-Zero)

- Perfect absorption: Destructive interference of reflected light (A = 1 – R – T)
- Critical coupling: $\gamma_{internal} = \gamma_{radiation}$
- ITO has the ENZ frequency in the near-IR (~ 1300 nm)



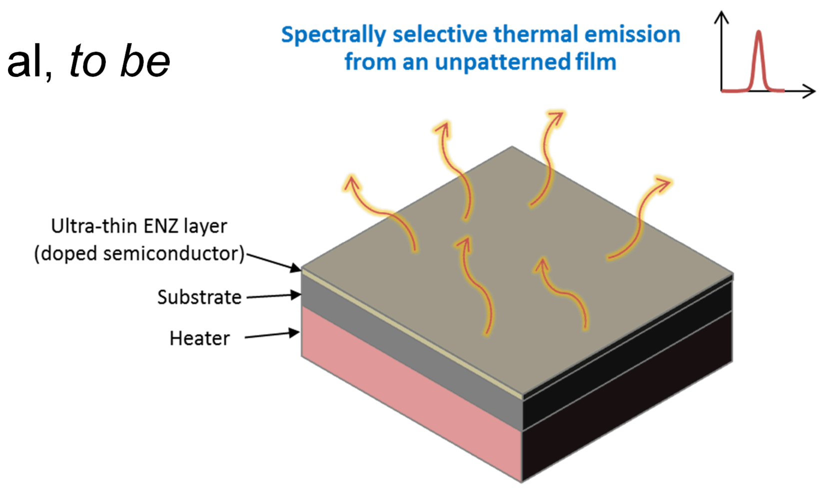


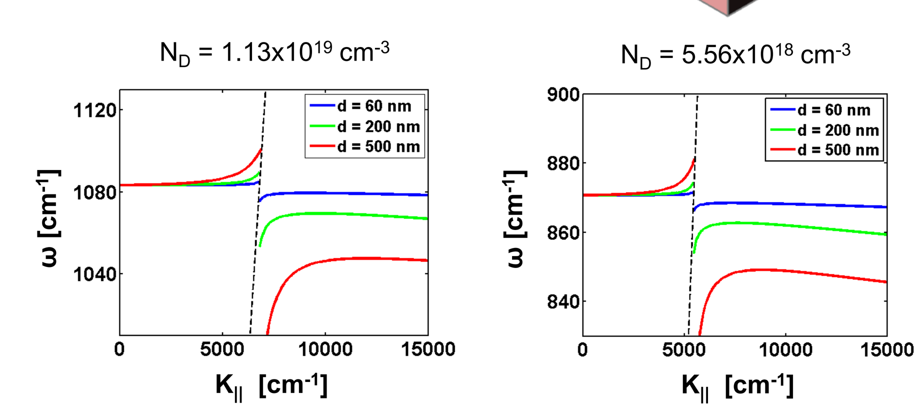
Experiment

ITO thickness	λ_{ENZ} (μm)	λ_{PA} (μm)	θ_{PA} (deg)	Absorption
24 nm	1.307	1.143	75.5	0.9979
53 nm	1.297	1.153	56.9	0.9998
88 nm	1.298	1.173	47	0.9996
137 nm	1.318	1.220	38.4	0.9996

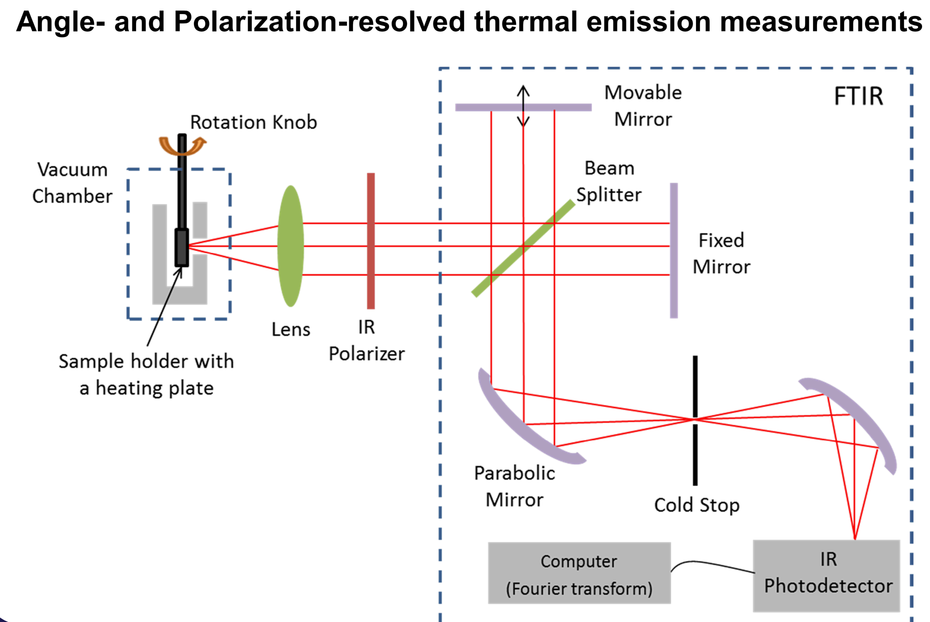
Narrowband Thermal Emission from an ENZ film

Y. C. Jun et al, *to be submitted*

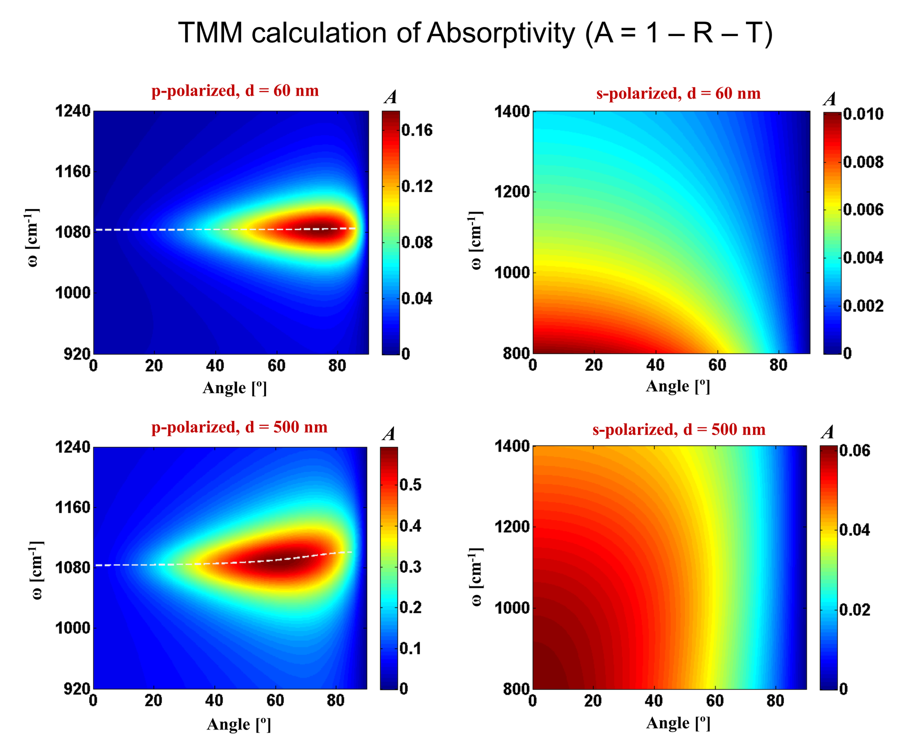


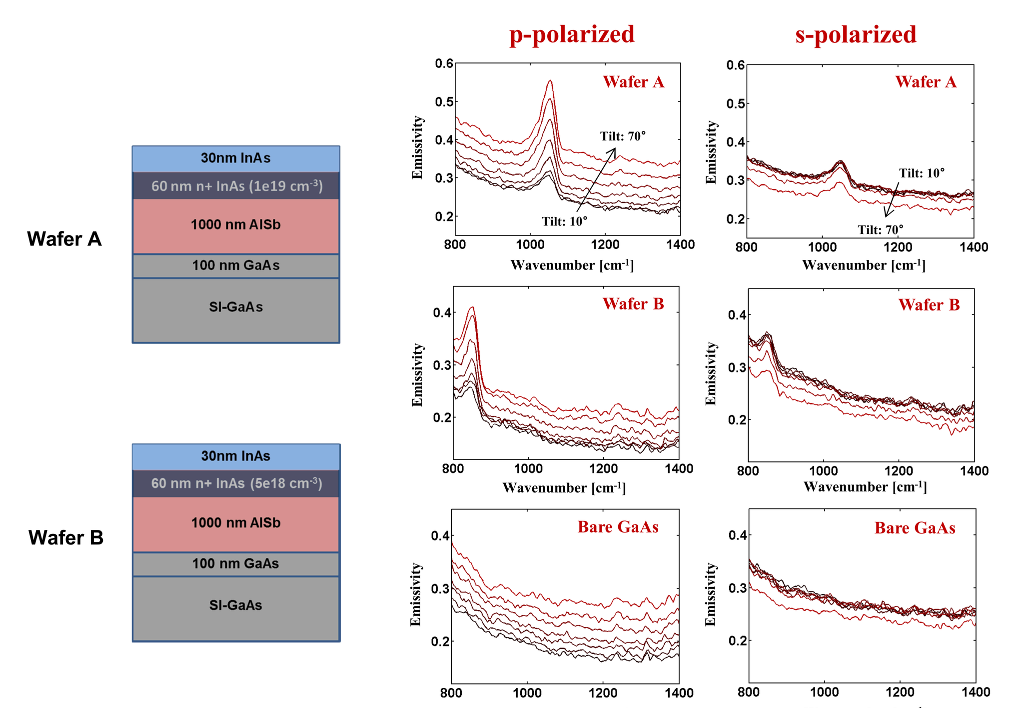


Angle- and Polarization-resolved thermal emission measurements



TMM calculation of Absorptivity (A = 1 – R – T)





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.

U.S. DEPARTMENT OF ENERGY
Office of Science