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Thermal Infrared Plasmonics

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Sandia National Labs

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Why Thermal Infrared?

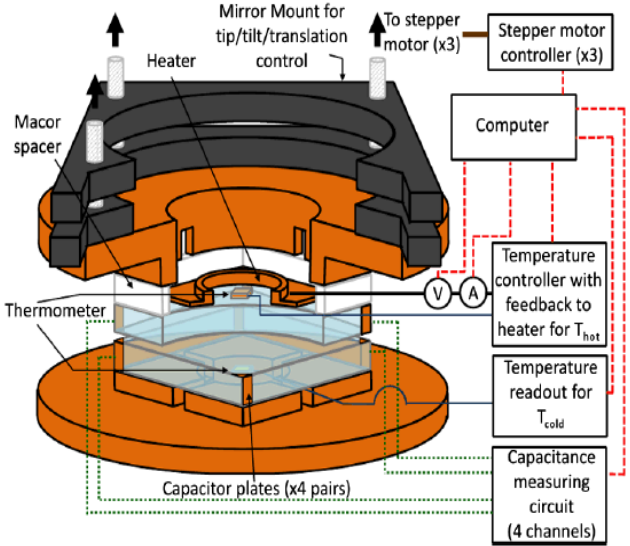
<u>LWIR region of spectrum 7-14 microns</u>

<u>Many applications</u>: thermal imaging, near field heat transfer, metamaterials …..

Near field radiative heat transfer

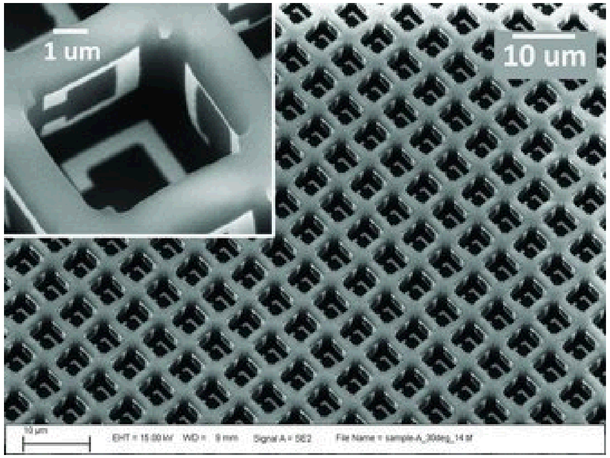
3D Metamaterials

Thermal Imaging



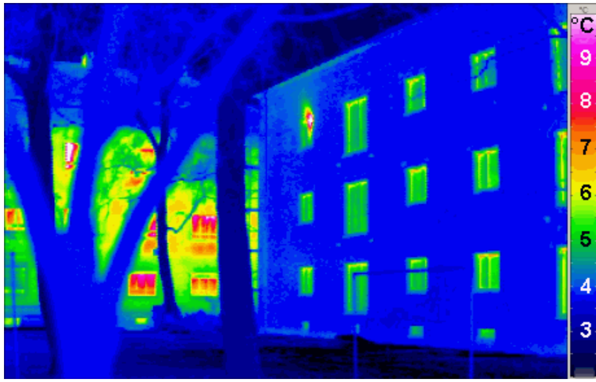
Near-field Radiative Heat transfer between Macroscopic Planar Surface

R. S. Ottens, et. al
PRL **107**, 014301 (2011)



Micrometer-Scale Cubic Unit Cell 3D Metamaterial Layers

D. Bruce Burckel et. al., **Adv. Mat.** [Volume 22, Issue 44,](#) 5053 (2010)



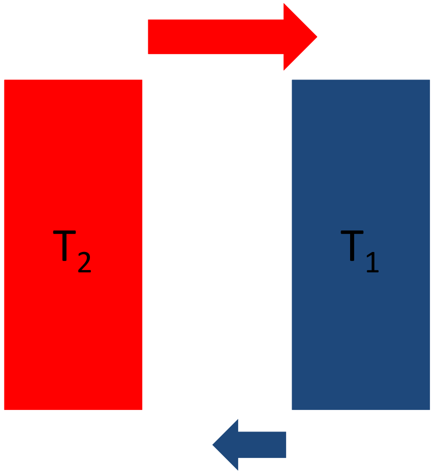
IR Camera's and Focal Plane Arrays

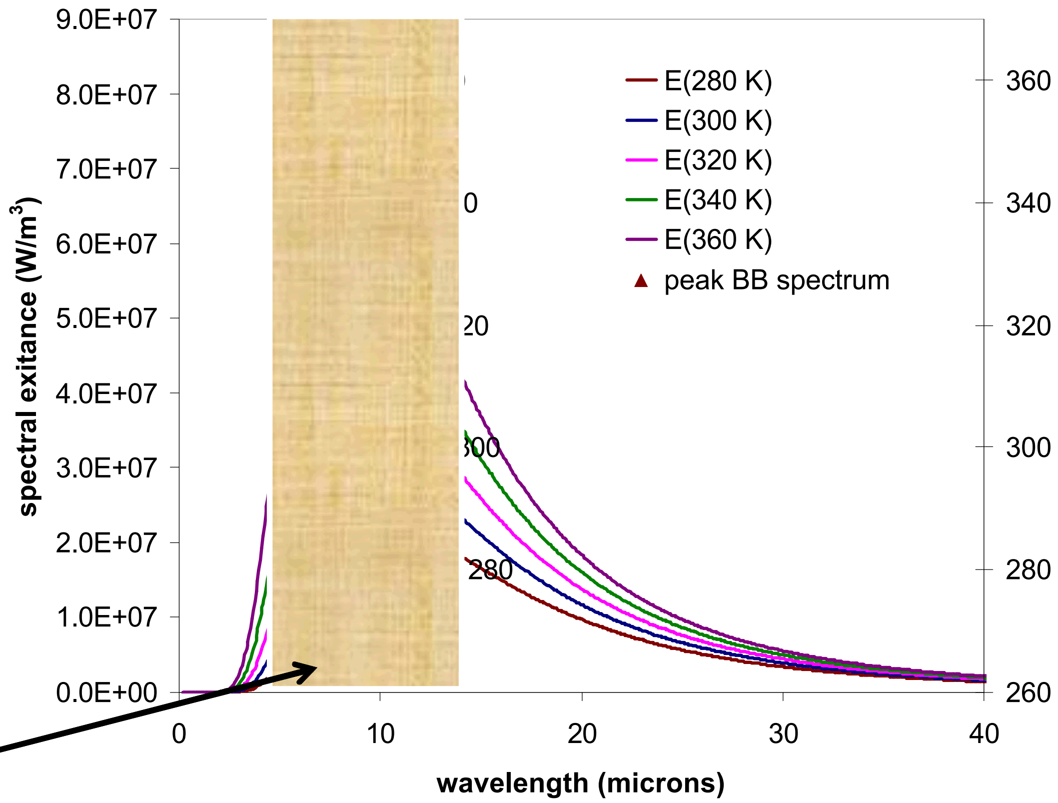
Thermal Radiation

Black-body Spectral Exitance

$$\mathcal{U}(\lambda,T) = \frac{d^2\mathscr{P}}{d\lambda\, dA} = \frac{2\pi hc^2}{\lambda^5}\frac{1}{\exp(\beta hc/\lambda)-1}.$$

Radiative Heat Transfer





Infrared Band of interest

Surface Plasmons in the Infrared

- **Interested in new active and passive devices in LWIR region of the spectrum:**
  - Near-field radiative heat transfer & Energy harvesting
  - Uncooled IR detectors for imaging
  - 3D metamaterials and frequency selective surfaces
- **What are plasmons?**
  - Collective excitations of free electron plasma in metal: Familiar from electron energy loss (EELS) spectroscopy.
- **Surface Plasmon Polaritons (SPP's):**
  - Electromagnetic bound modes at a metal dielectric interface.
- **What are SPP's good for?**
  - Strongly confine light to metal/dielectric interface.
  - Guide light at interface and propagate with reasonably low loss.
  - Field enhancement in small gaps and resonances. (optical)
- **We are interested in enhancing confinement in LWIR (7-14 μm)**
  - Two approaches: change plasma frequency, and or high index dielectrics.

Metals in the Infrared

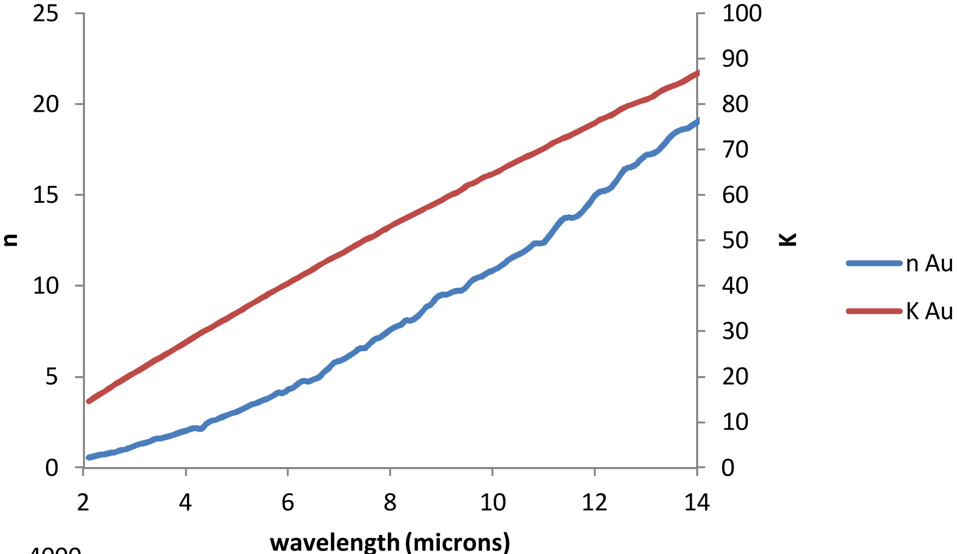
Metal: Free Electron Drude Model

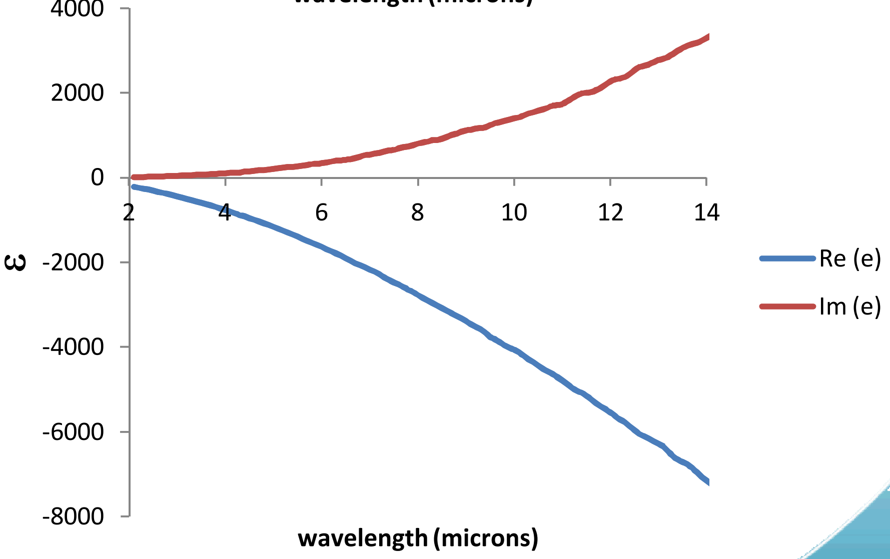
$$\varepsilon(\omega) = \varepsilon_0\left(1 - i\frac{\omega_{pl}^2}{\gamma(\omega + i\gamma)} + i\frac{\omega_{pl}^2}{\gamma\omega}\right)$$

$$\sigma = \frac{\omega_{pl}^2}{4\pi\gamma} = \frac{e^2 n\tau}{m}$$

Pole at ω=0, represents metal with finite conductivity,

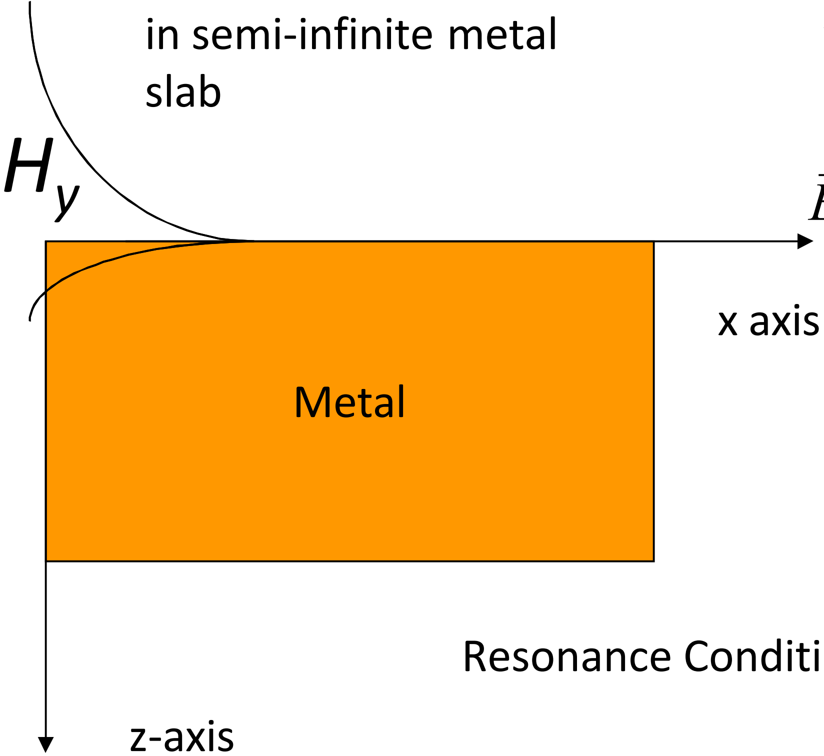
Au as representative metal in LWIR.





Surface Plasmons: EM surface eigenmodes

p-polarized eigenmodes
in semi-infinite metal
slab



$$\vec{E}_c = \frac{E_0}{k\sqrt{\varepsilon_c}}\left(\gamma_c\hat{e}_x + k_x\hat{e}_z\right)\exp(ik_x x - i\gamma_c z)$$

$$\vec{E}_m = \frac{E_m}{k\sqrt{\varepsilon_m}}\left(-\gamma_m\hat{e}_x + k_x\hat{e}_z\right)\exp(ik_x x + i\gamma_m z)$$

Boundary Conditions at z=0 :
Tangential components of E
Normal components of D

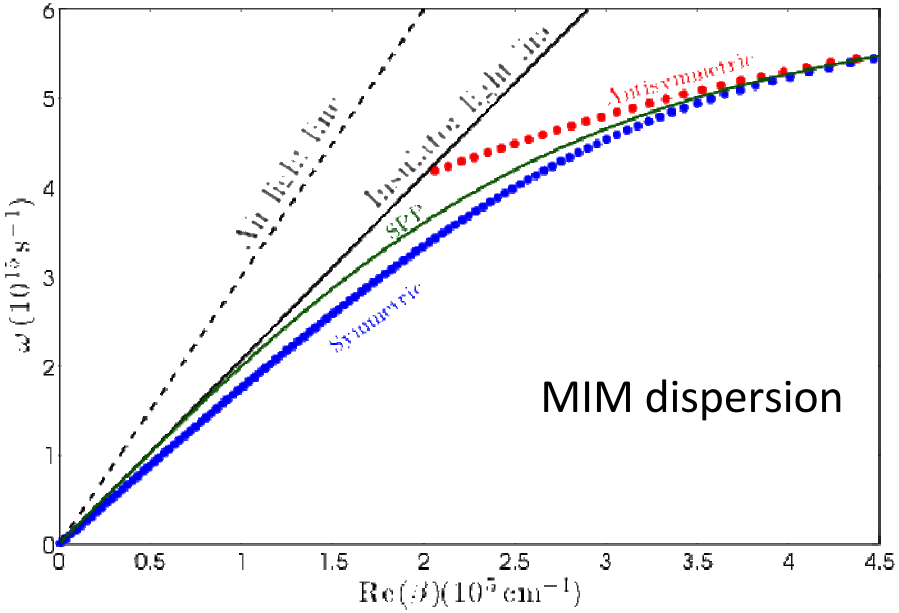
Resonance Condition

SPP Dispersion relationship

$$-\frac{\gamma_m}{\gamma_d} = \frac{\varepsilon_m}{\varepsilon_d} \longrightarrow \boxed{k_x = k\sqrt{\frac{\varepsilon_d\varepsilon_m}{\varepsilon_d + \varepsilon_m}}}$$

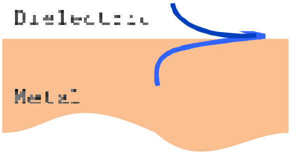
P.S. Davids

Surface Plasmon Dispersion



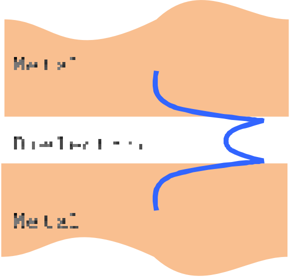
MIM dispersion

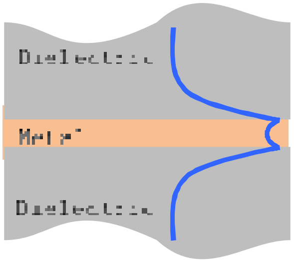
Single Interface SPP

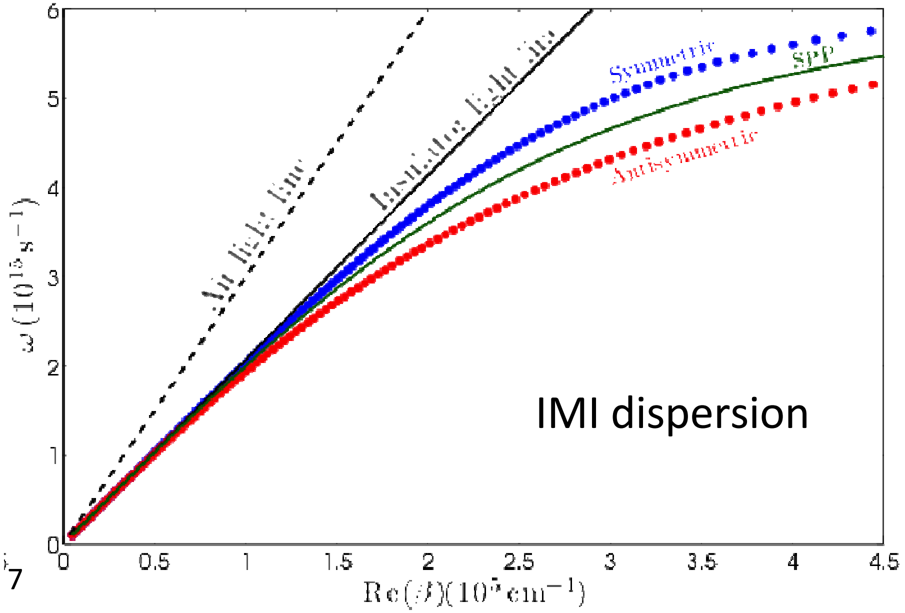


MIM

IMI



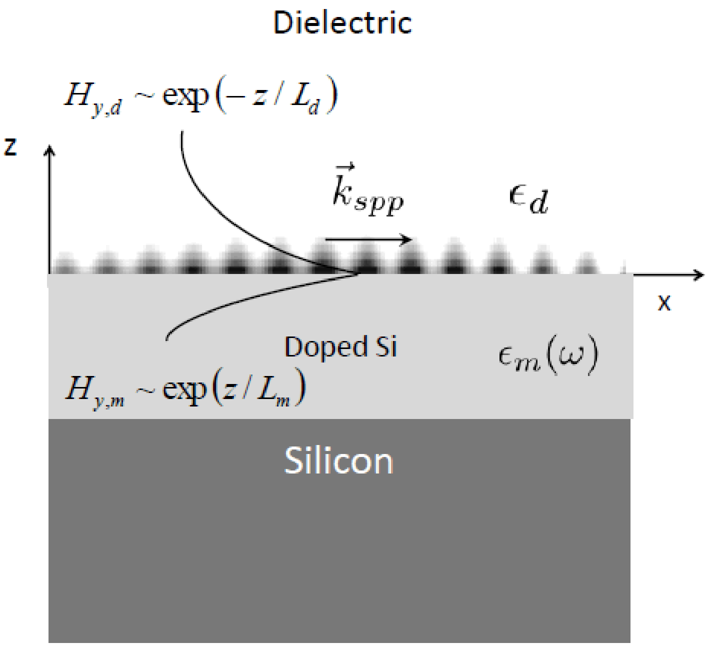




IMI dispersion

Surface Plasmon Confinement

Surface Plasmons confine light strongly to surface.



$$H_{y,d} \sim \exp(-z/L_d) \quad \text{for z} \geq 0$$
$$H_{y,m} \sim \exp(z/L_m) \quad \text{for z} < 0$$

Characteristic Confinement Length.

$$L_i = 1/\left|Im(\gamma_i)\right|$$

$$\gamma_i = k\sqrt{\frac{\epsilon_i^2}{\epsilon_d + \epsilon_m}}.$$

$$L_d = \mathrm{Im}\left(\frac{\sqrt{\varepsilon_m + \varepsilon_d}}{k\varepsilon_d}\right)$$

$$L_m = \mathrm{Im}\left(\frac{\sqrt{\varepsilon_m + \varepsilon_d}}{k\varepsilon_m}\right)$$

We want L_d (and L_m) small (highly confine):

2 options:

1. Make ε_m smaller and negative.
2. Make ε_d large.

Option 1: Modify metal in IR

- Metal Plasma frequency depends on free-carrier concentration.
- Can’t modulate metal free carrier concentration.
  - Plasma frequency fixed in UV-Visible
- Can modulate free-carrier concentration in a doped semi-conductor.

$$\varepsilon(\omega) = \varepsilon_0 \left(1 - i \frac{\omega_{pl}^2}{\gamma(\omega + i\gamma)} + i \frac{\omega_{pl}^2}{\gamma\omega} \right)$$

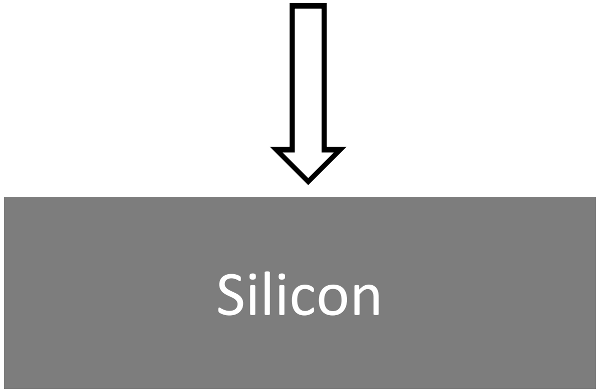
$$\sigma = \frac{\omega_{pl}^2}{4\pi\gamma} = \frac{e^2 n\tau}{m}$$

n is free-carrier concentration.
τ is collision time.

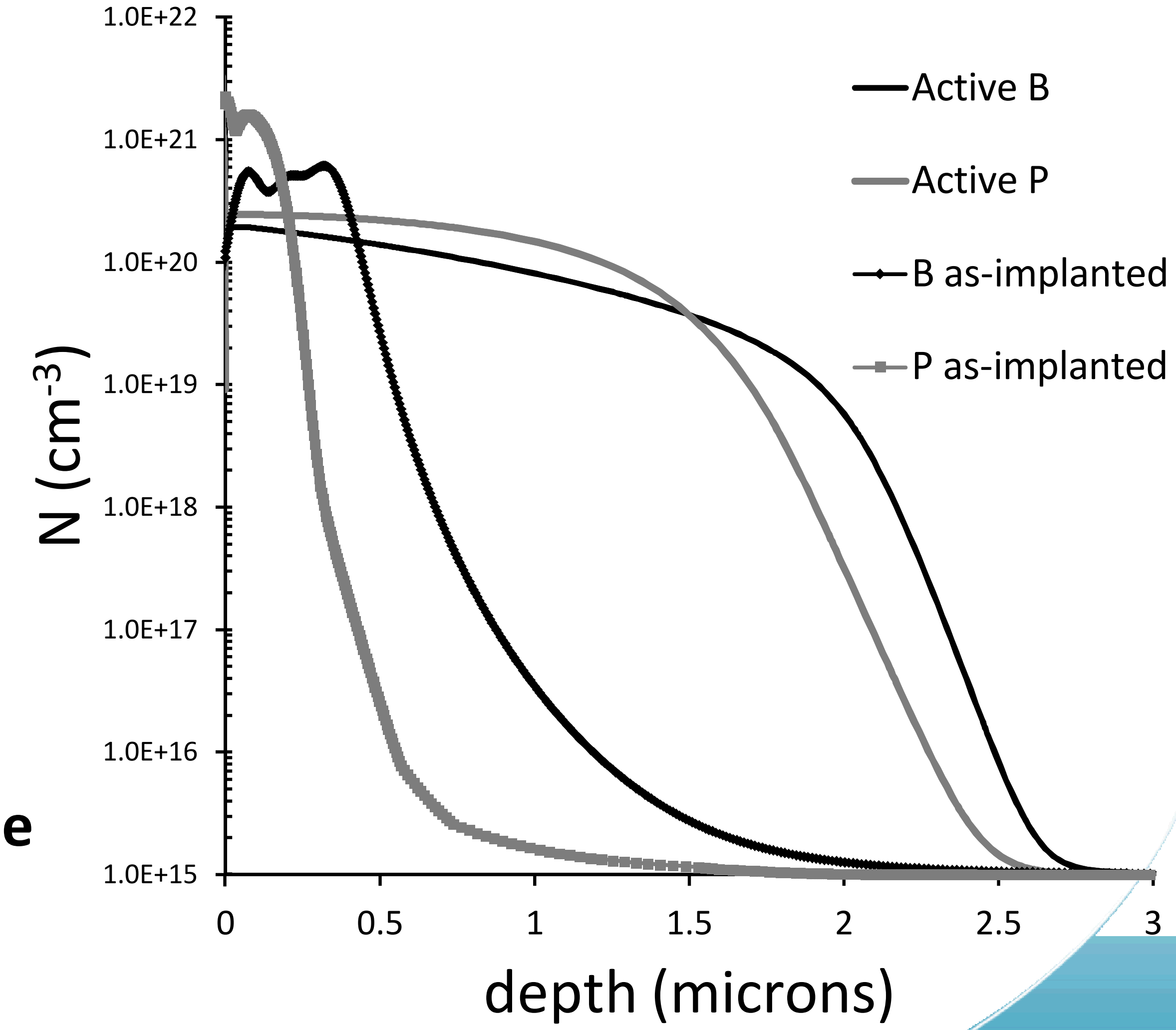
Examine optical properties of heavily-Doped Si

Heavily-doped Silicon

Ion-implant : Boron (p-type) or Phosphorus (n-type)



Standard CMOS Processing
Well developed process



What is the impact on the IR optical properties?

Implant Dose & Anneal

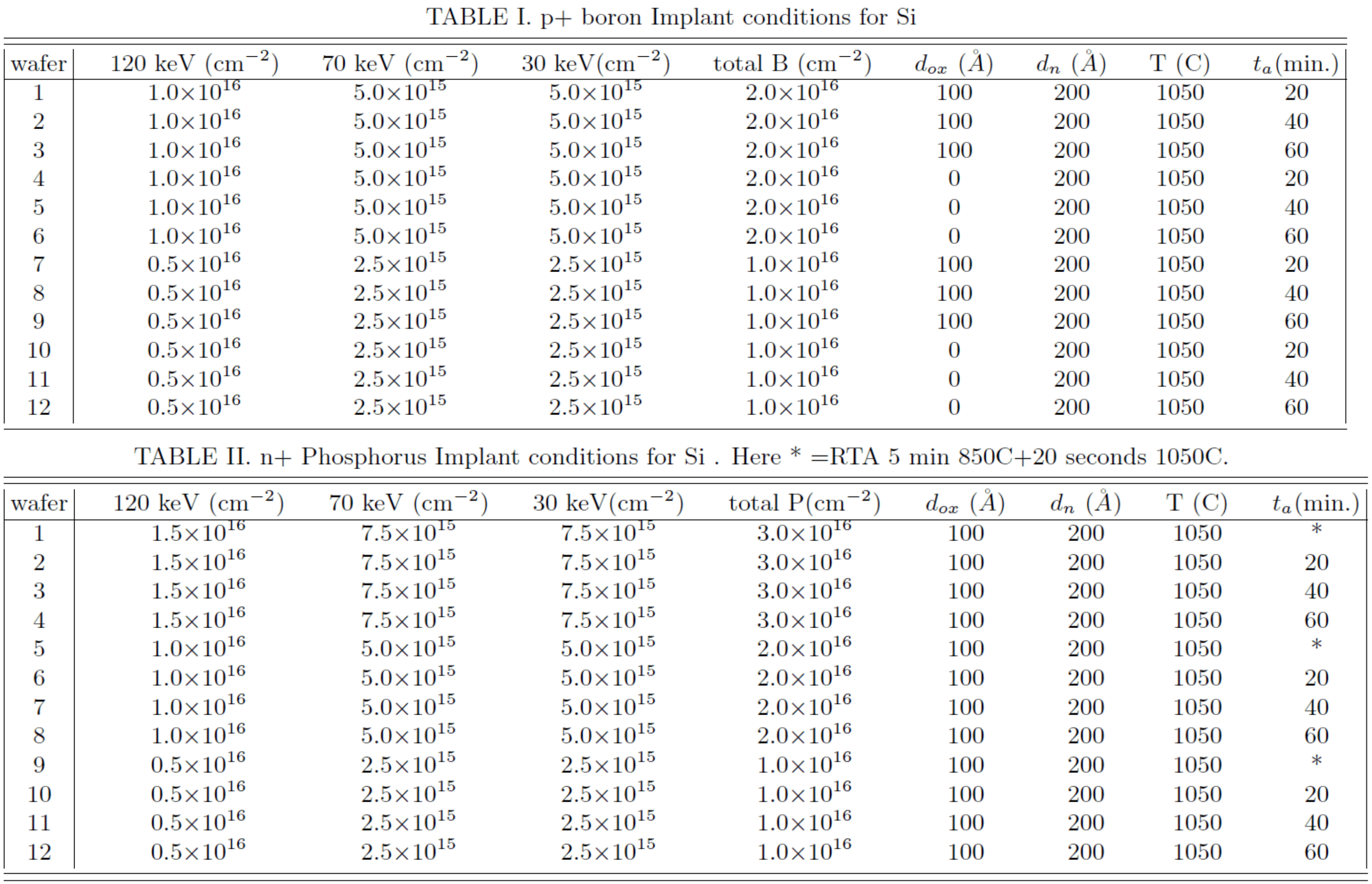


TABLE I. p+ boron Implant conditions for Si

wafer	120 keV (cm^{-2})	70 keV (cm^{-2})	30 keV(cm^{-2})	total B (cm^{-2})	d_{ox} (Å)	d_n (Å)	T (C)	t_a(min.)
1	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	20
2	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	40
3	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	60
4	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	0	200	1050	20
5	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	0	200	1050	40
6	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	0	200	1050	60
7	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	20
8	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	40
9	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	60
10	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	0	200	1050	20
11	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	0	200	1050	40
12	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	0	200	1050	60

TABLE II. n+ Phosphorus Implant conditions for Si . Here * =RTA 5 min 850C+20 seconds 1050C.

wafer	120 keV (cm^{-2})	70 keV (cm^{-2})	30 keV(cm^{-2})	total P(cm^{-2})	d_{ox} (Å)	d_n (Å)	T (C)	t_a(min.)
1	1.5×10^{16}	7.5×10^{15}	7.5×10^{15}	3.0×10^{16}	100	200	1050	*
2	1.5×10^{16}	7.5×10^{15}	7.5×10^{15}	3.0×10^{16}	100	200	1050	20
3	1.5×10^{16}	7.5×10^{15}	7.5×10^{15}	3.0×10^{16}	100	200	1050	40
4	1.5×10^{16}	7.5×10^{15}	7.5×10^{15}	3.0×10^{16}	100	200	1050	60
5	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	*
6	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	20
7	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	40
8	1.0×10^{16}	5.0×10^{15}	5.0×10^{15}	2.0×10^{16}	100	200	1050	60
9	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	*
10	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	20
11	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	40
12	0.5×10^{16}	2.5×10^{15}	2.5×10^{15}	1.0×10^{16}	100	200	1050	60

Infrared Plasmons on Heavily-Doped Silicon

James C. Ginn,[1, a)] Robert L. Jarecki Jr.,[1] Eric A. Shaner,[1] and Paul S. Davids[1, b)]
Applied Photonics and Microsystems
Sandia National Laboratory

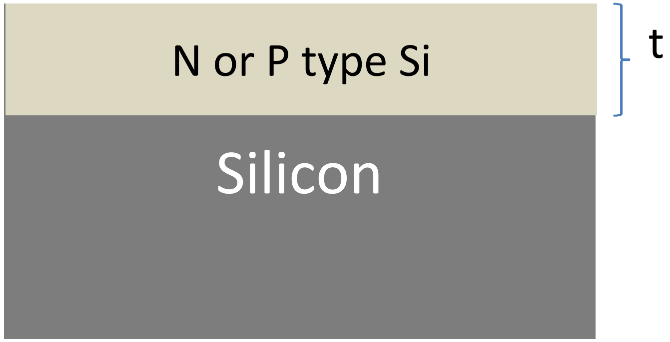
to appear in J. Appl. Phys.

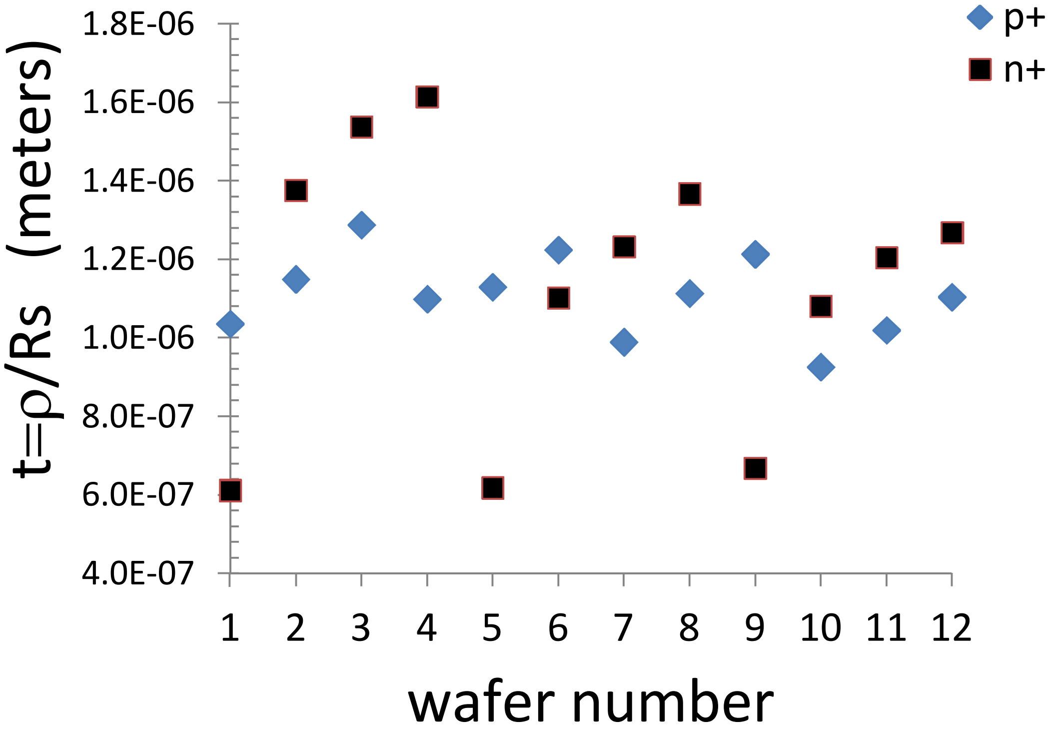
Activation of Dopants

R_s Sheet resistance

$$1/\rho \sim \omega_{pl}^2 \tau$$

Drude resistance

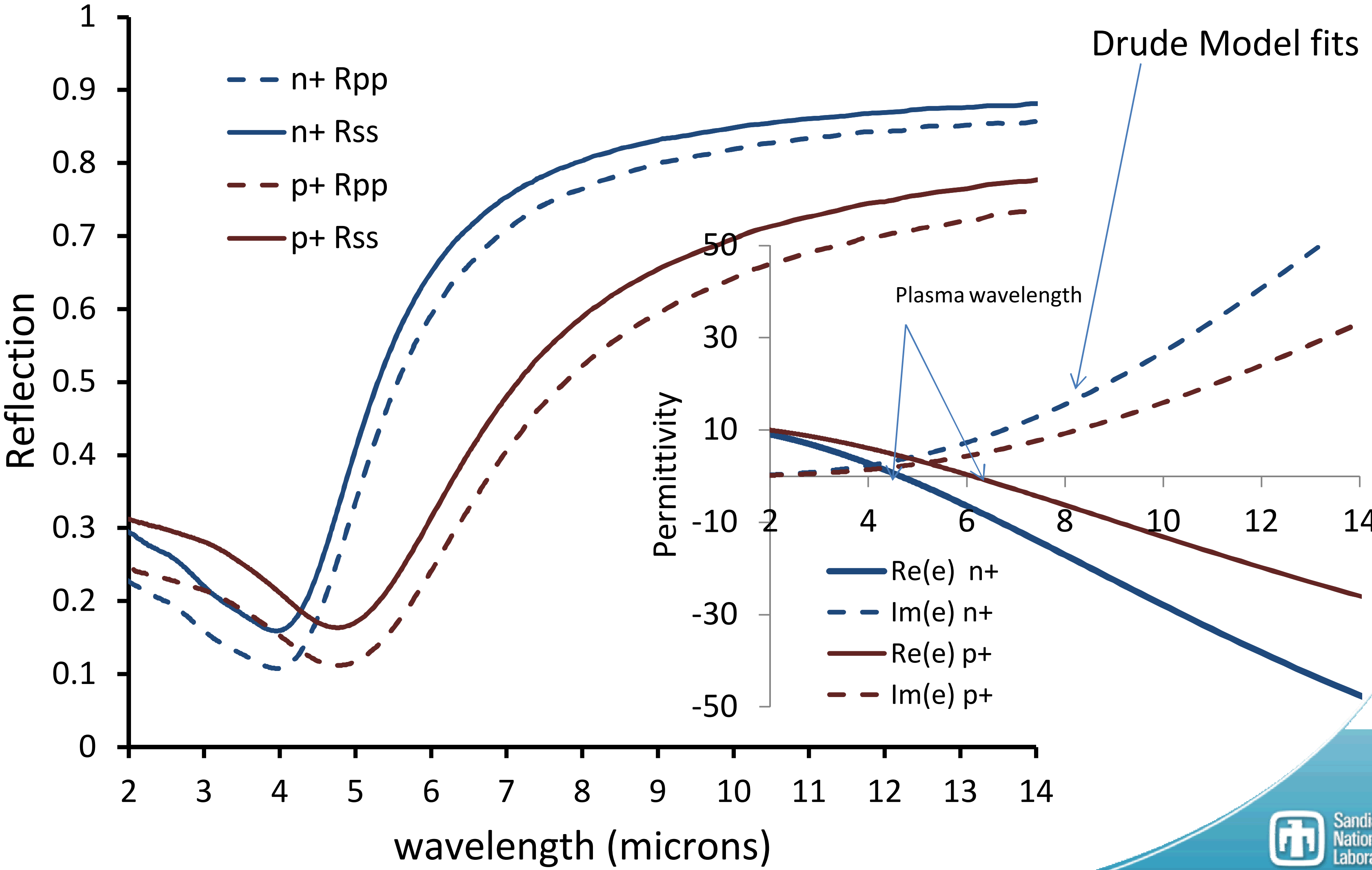




Level of Activation correlates with implant dose and RTA anneal temperature and time.

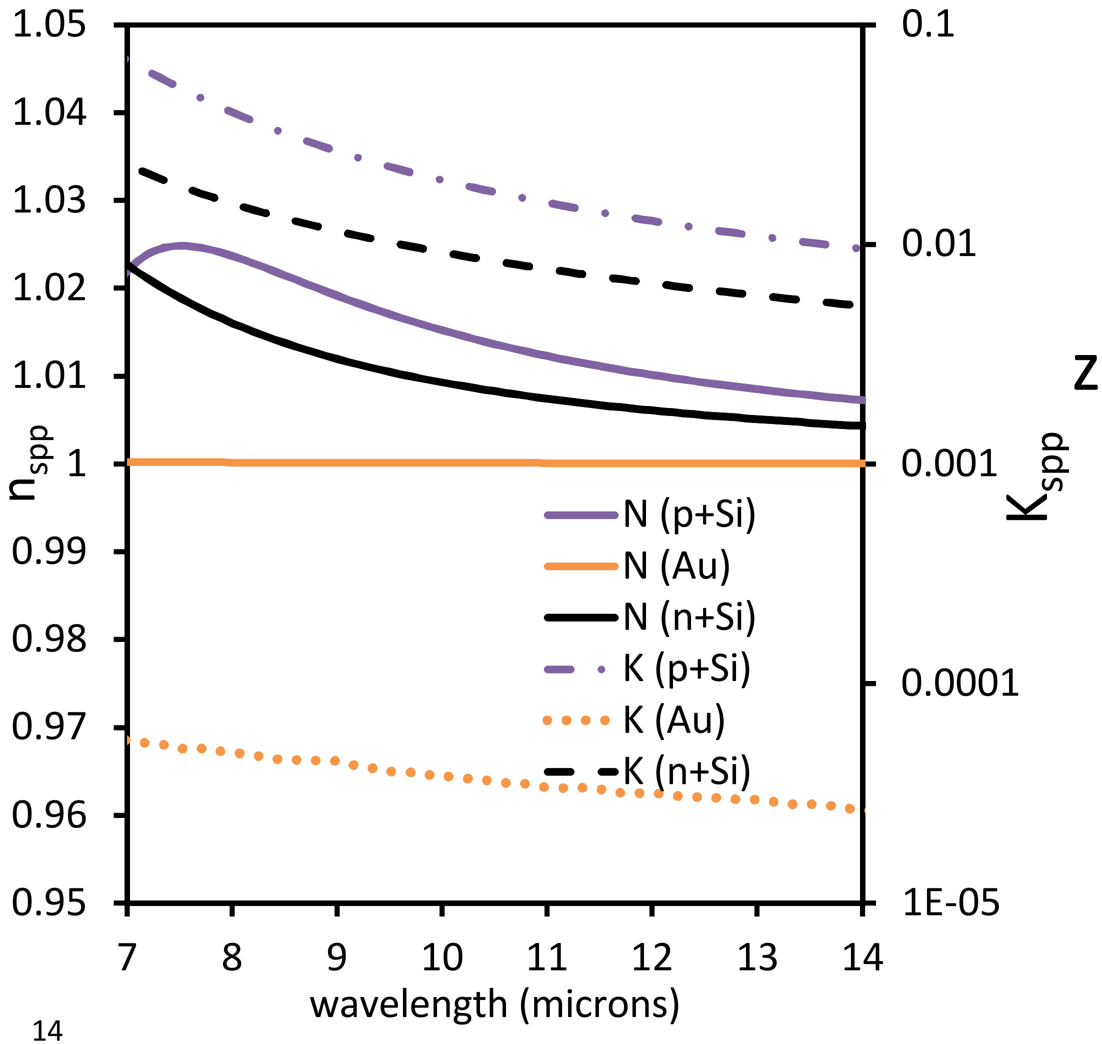
Optical Properties of Heavily-doped Si

Measure optical response of doped Si layer using IR VASE.



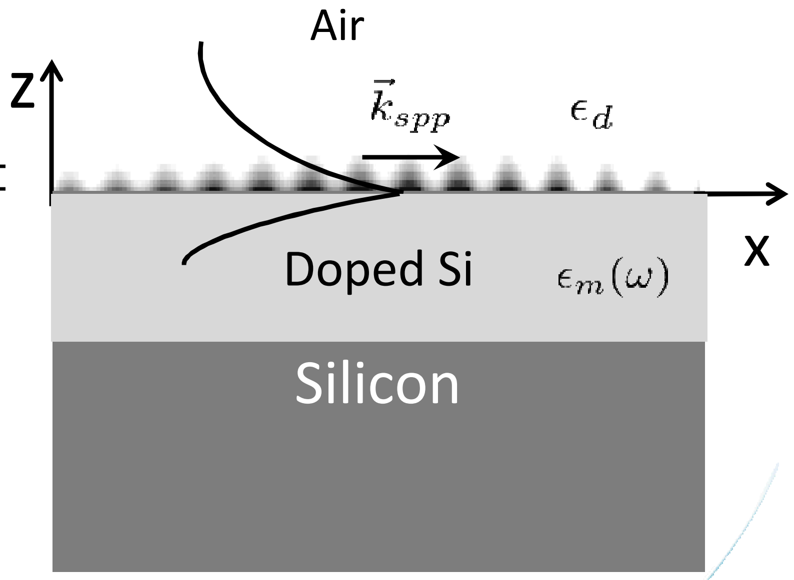
Surface Plasmons on Heavily Doped Si

From extracted Drude Model parameters

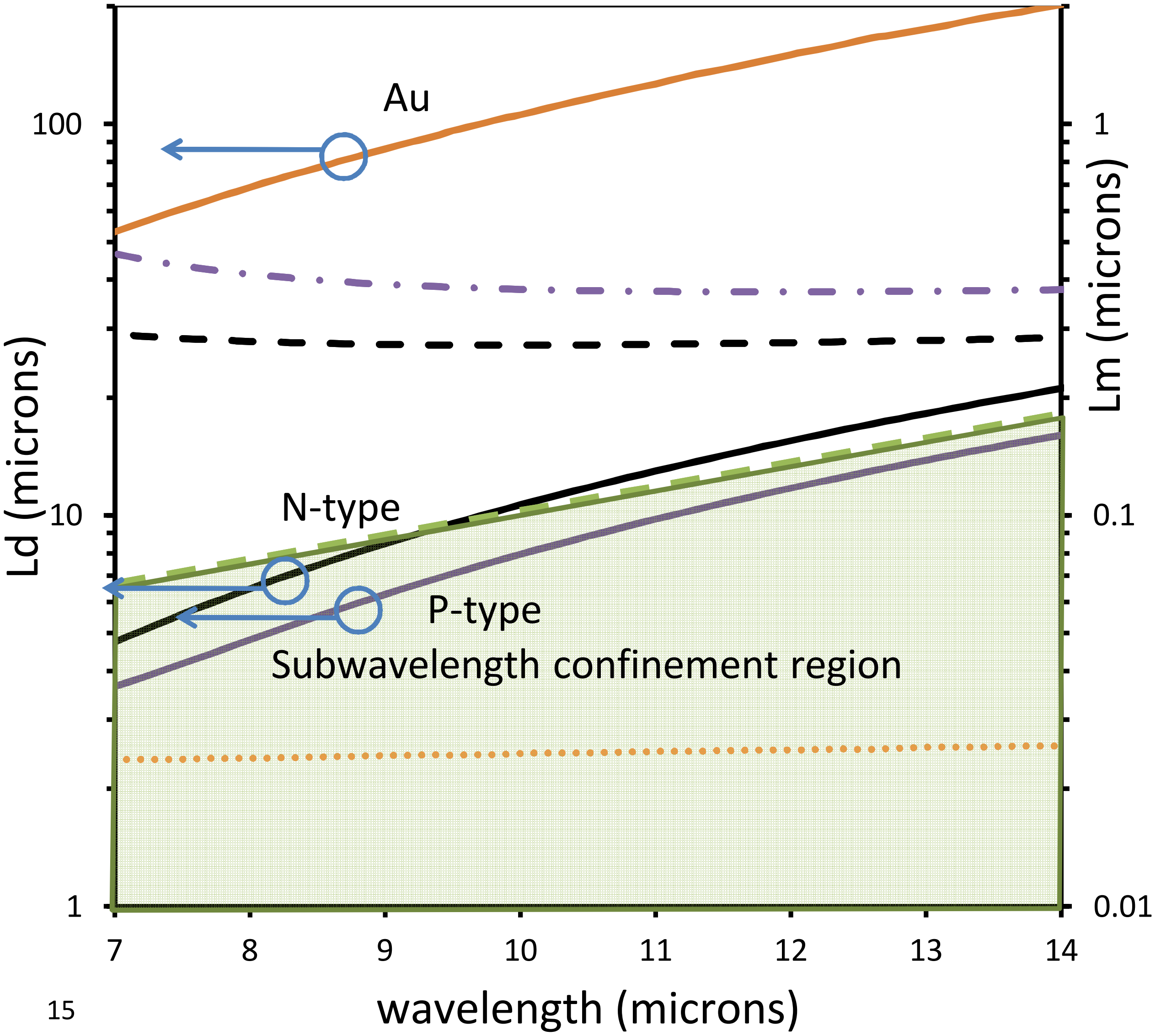


$$\epsilon_m(\omega) = \epsilon_{\text{Si}} \left(1 + \frac{i\omega_{pl}^2 \tau}{\omega(1 - i\omega\tau)} \right)$$

$$k_{spp} = k\left(n_{spp} + iK_{spp}\right)$$



Surface Plasmon confinement



Sub-wavelength confinement in air for p-type over entire range.

Sub-wavelength confinement for n-type < 9.5 microns.

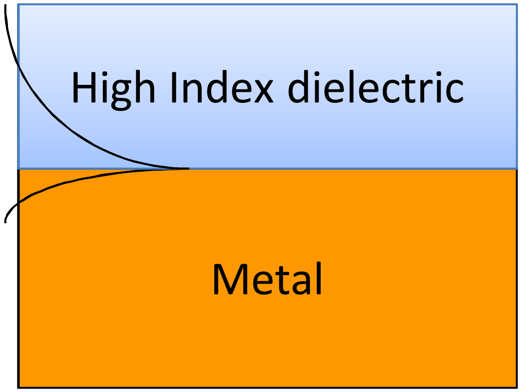
Au SPP is very extended into air.

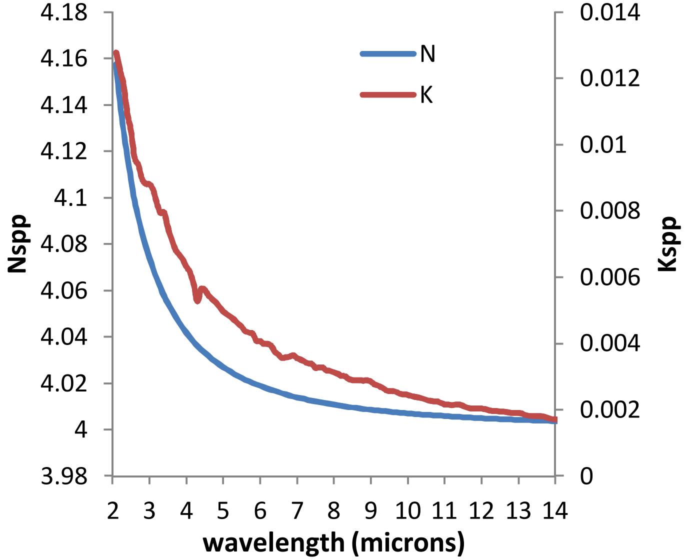
Summary: Doped Si Plasmons

- **Strong confinement at Si dielectric interface.**
- **Traded off confinement for propagation loss.**
- **Smooth interface (Crystal Si wafer)**
- **CMOS compatible and integration with active devices possible.**

Option 2: High Index Dielectric

Germanium: ε =16 will improve confinement of IR by factor of 16.

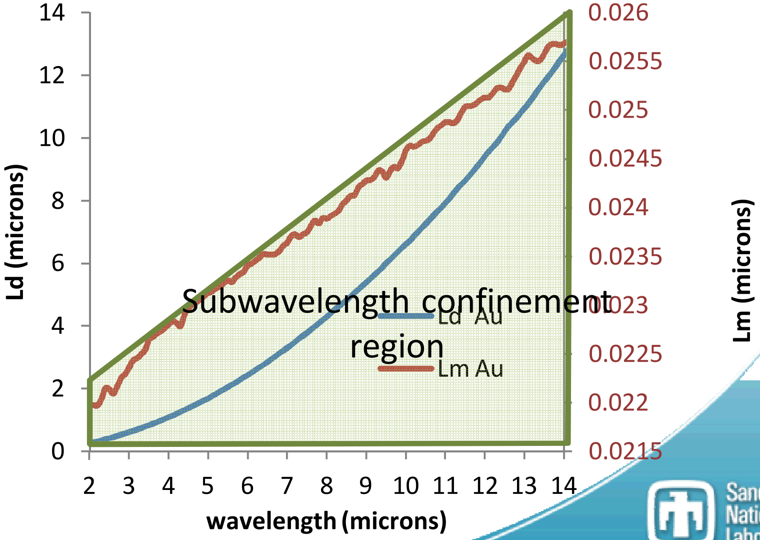




No Impact on SPP loss.

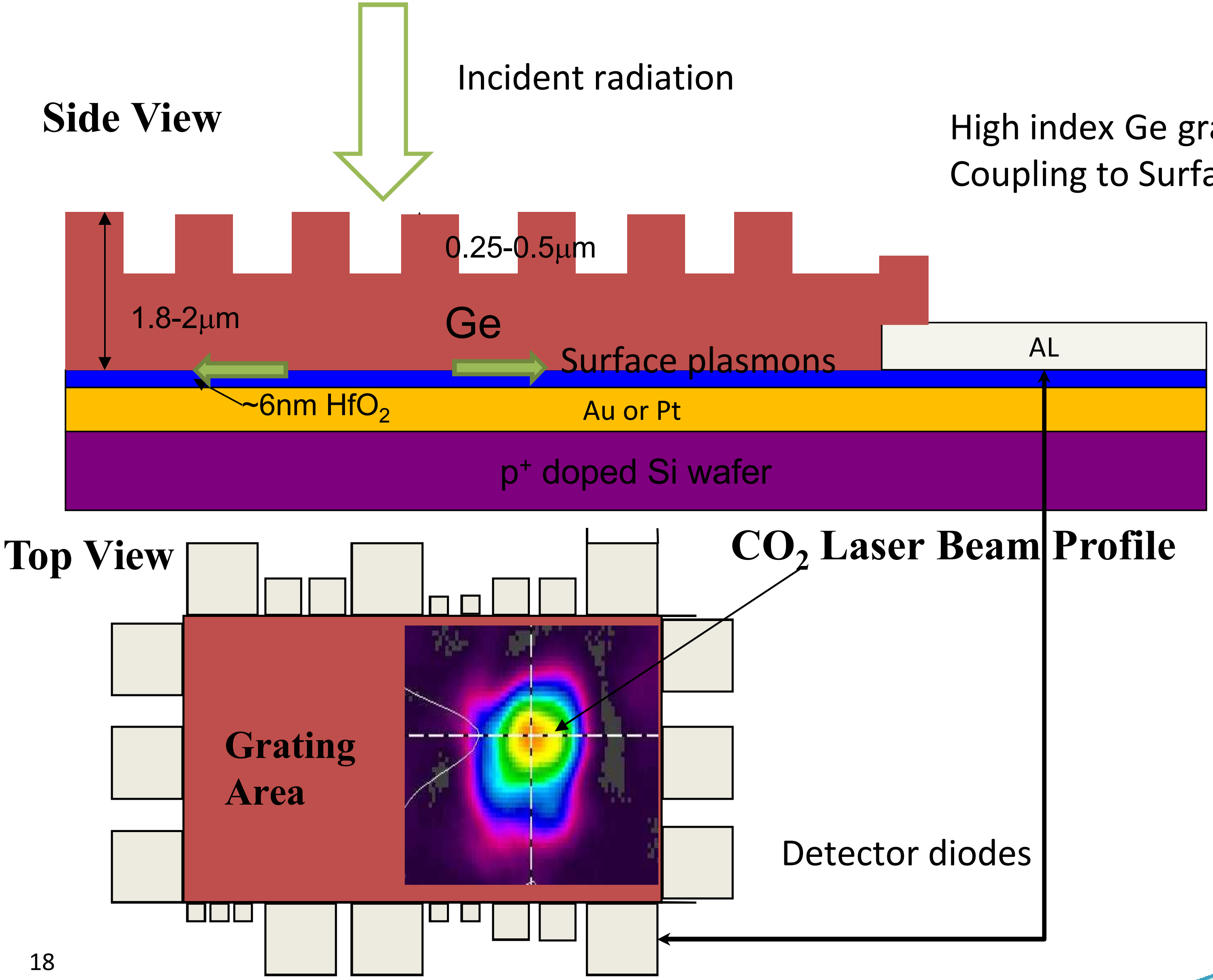
Sub-wavelength confinement (free-space)

Enhanced SPP confinement due to high Index dielectric.



Examine grating coupling into IR-SPP at metal surface.

Grating Coupling to Surface Plasmons



Side View

Incident radiation

0.25-0.5μm

1.8-2μm

Ge

Surface plasmons

AL

~6nm HfO_2

Au or Pt

p^+ doped Si wafer

Top View

CO_2 Laser Beam Profile

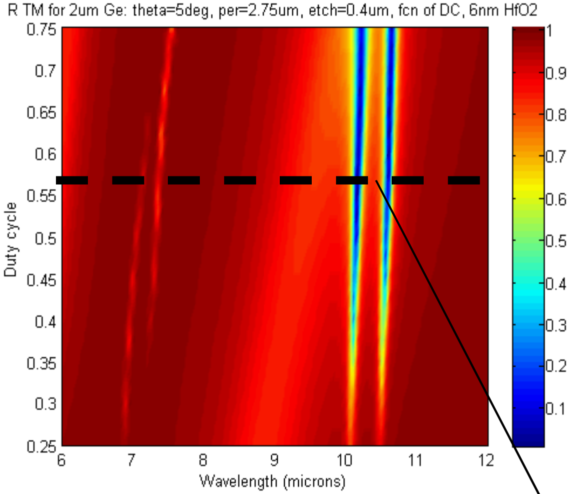
Grating Area

Detector diodes

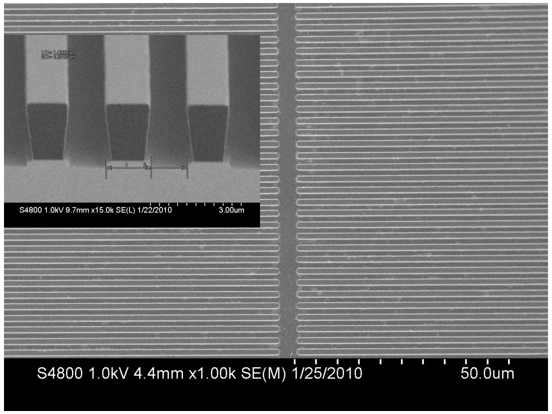
High index Ge grating
Coupling to Surface Plasmons

Grating Design

Minimize TM reflection from Grating stack

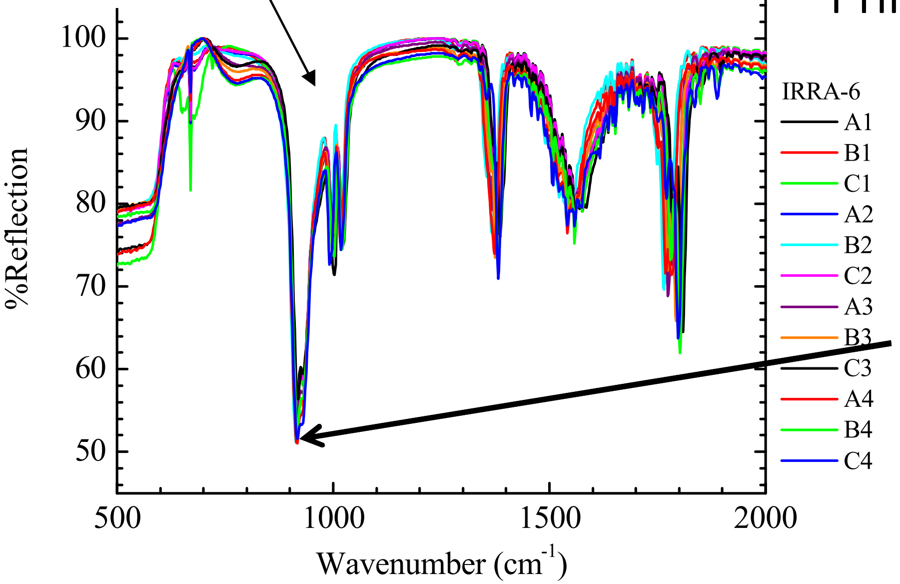


Fabricate large area grating



FTIR measurement of grating

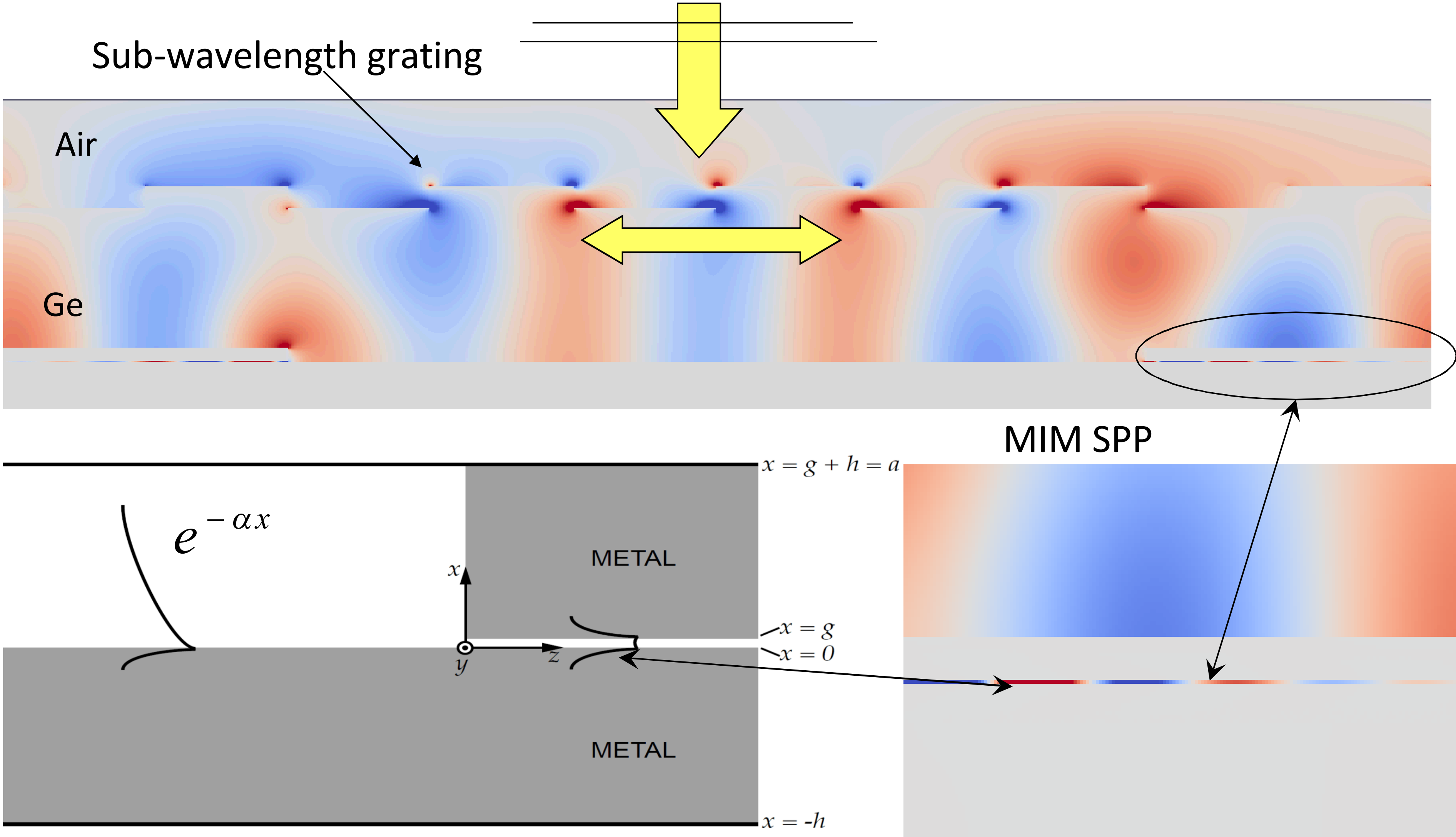
5^0 Off-normal



TM polarized reflection null

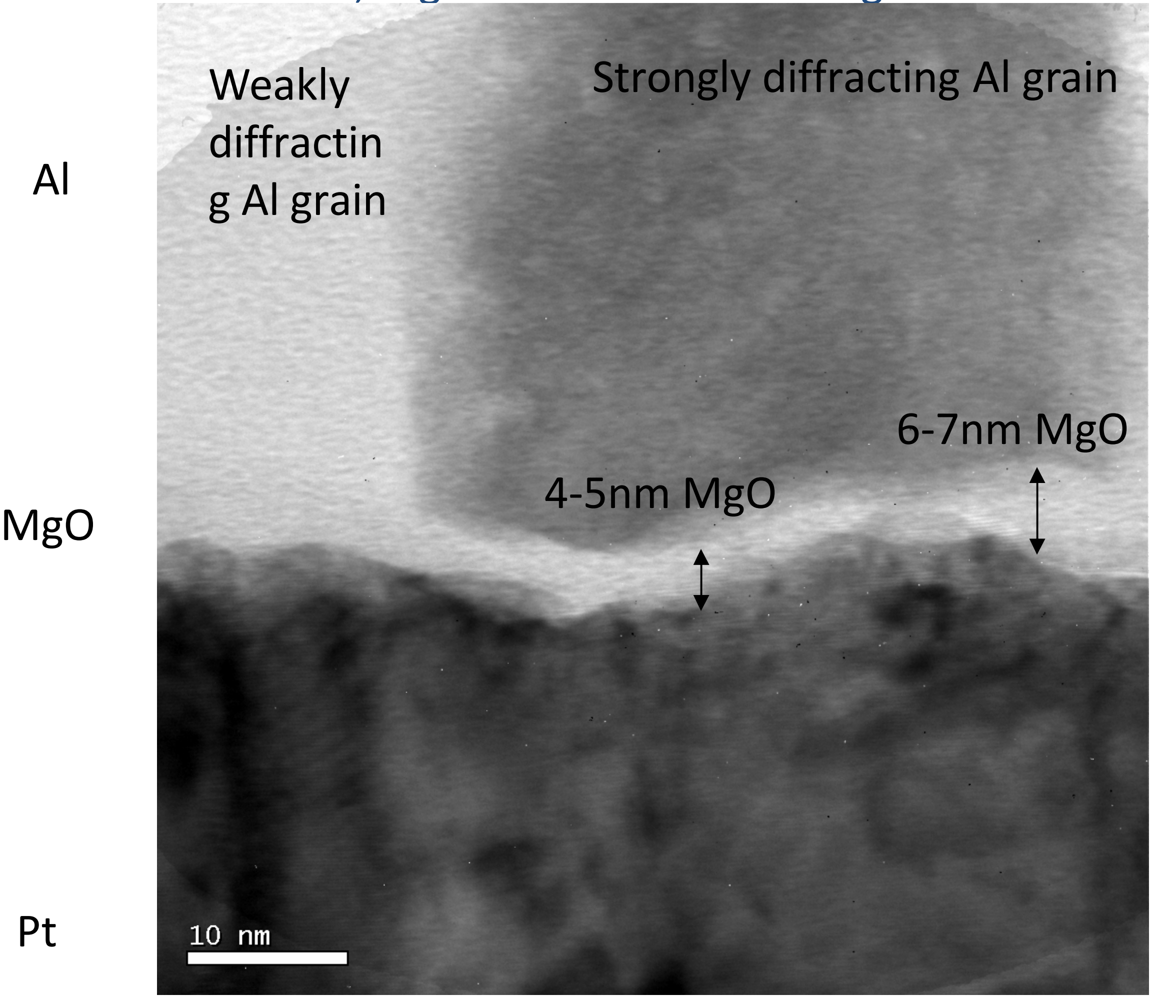
<u>Surface plasmon excitation</u>

Enhanced SPP confinement in IR



Surface Roughness at Metal interface

Diode, High-resolution TEM image



Metal Insulator Metal Detector structure.

Underlying surface roughness of Pt causes SPP scattering.

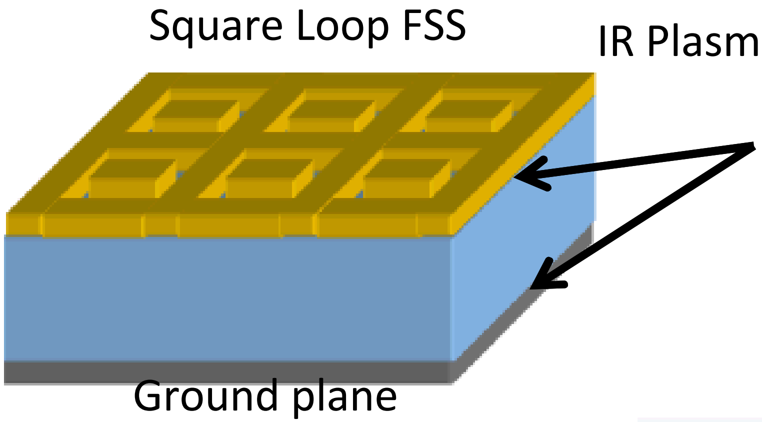
Excessive loss.

Solution: Use heavily doped Si outlined previously for smooth Surface for plasmon propagation.

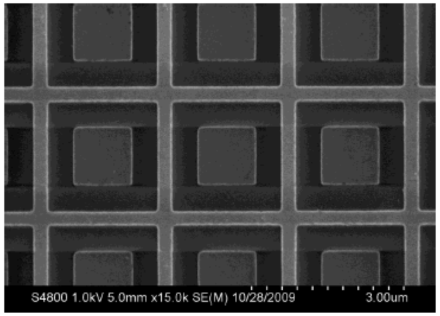
Summary: High index dielectrics & SPP’s

- **Strong confinement at metal dielectric interface.**
  - Confinement is limited by high index dielectric (which is Ge at ε=16)
- **Low propagation loss.**
- **Surface roughness and scattering is dominant mechanism for propagation loss.**

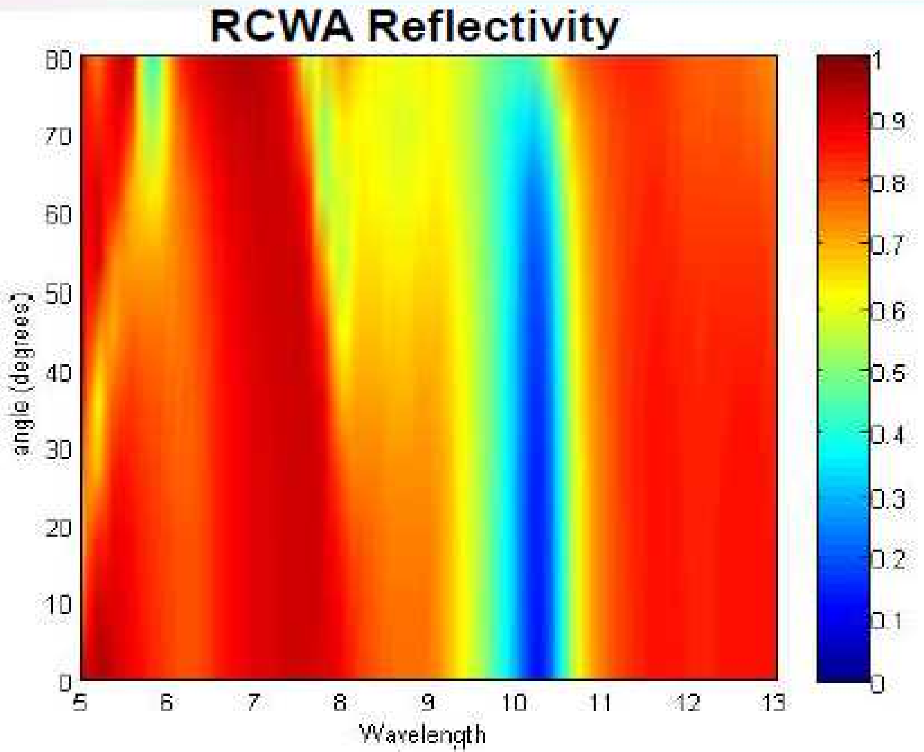
Infrared Frequency Selective Absorbers

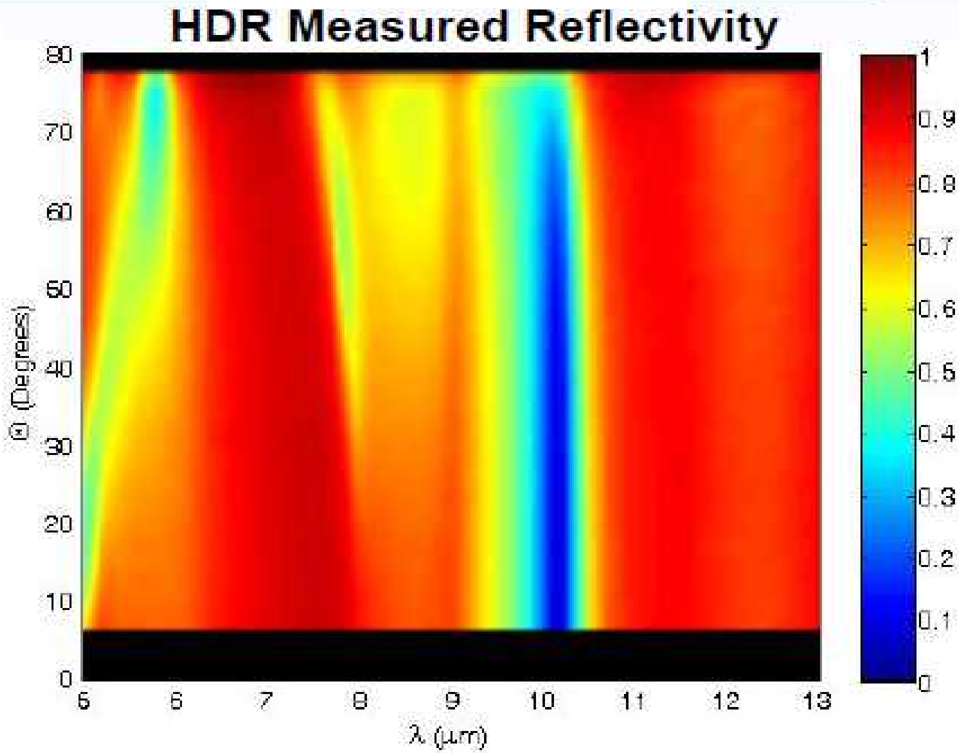


IR Plasmons confine light to interfaces.



SiO_2


RCWA Reflectivity


HDR Measured Reflectivity

Summary

- **Demonstrated engineering of plasma frequency by doping in Si.**
  - Shifted to LWIR.
- **Examined Surface Plasmon Polaritons in LWIR**
- **Two methods for enhanced confinement**
  - Heavily doped Si (metallic behavior in LWIR)
  - High index dielectric/metal surface.
  - Can combine to get super confined SPP modes in LWIR.
- **Demonstrated Grating coupling into LWIR SPP's and novel FSS absorbers**
- **Potential for active SPP devices in LWIR using CMOS compatible heavily doped Si as plasmonic metal.**

Acknowledgements

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All with Sandia National Labs.

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Sheet Resistance

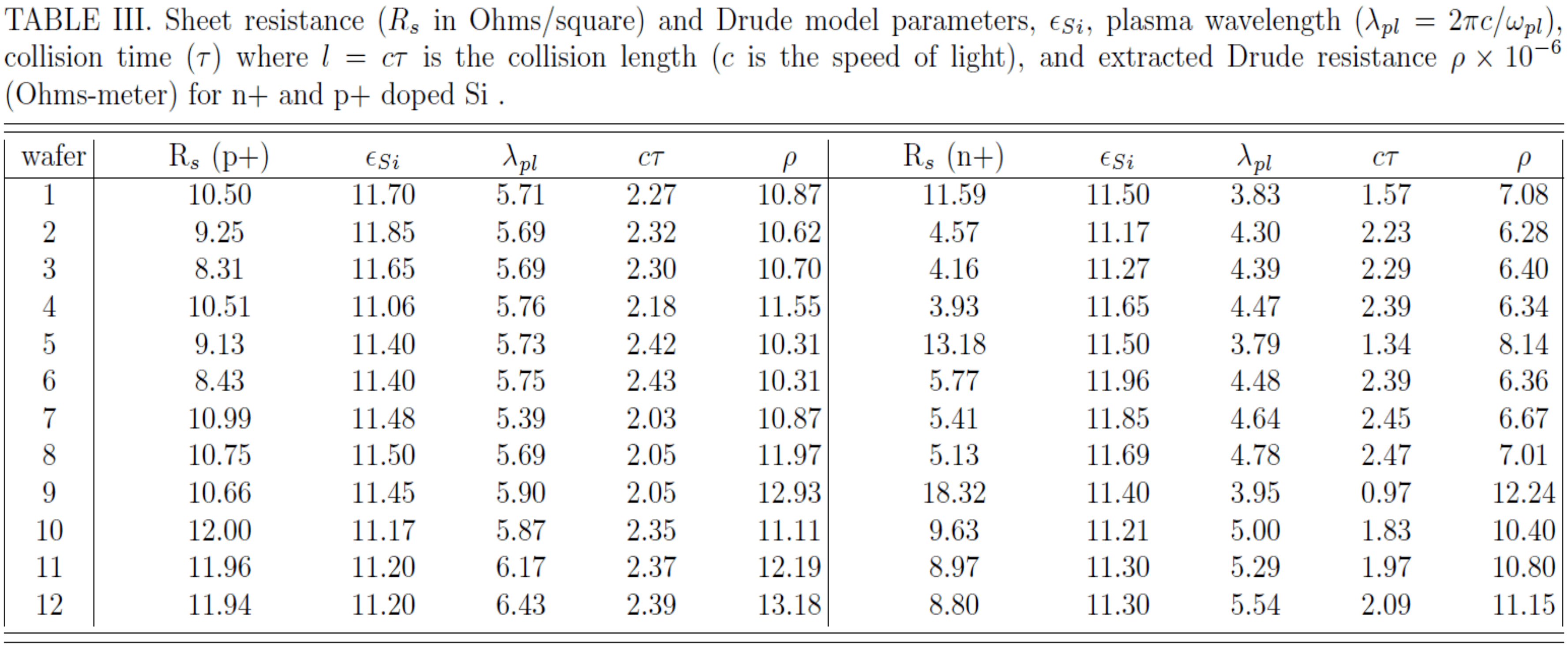

TABLE III. Sheet resistance (R_s in Ohms/square) and Drude model parameters, ϵ_{Si}, plasma wavelength ($\lambda_{pl} = 2\pi c/\omega_{pl}$), collision time ($\tau$) where $l = c\tau$ is the collision length (c is the speed of light), and extracted Drude resistance $\rho \times 10^{-6}$ (Ohms-meter) for n+ and p+ doped Si .

wafer	R_s (p+)	ϵ_{Si}	λ_{pl}	$c\tau$	ρ	R_s (n+)	ϵ_{Si}	λ_{pl}	$c\tau$	ρ
1	10.50	11.70	5.71	2.27	10.87	11.59	11.50	3.83	1.57	7.08
2	9.25	11.85	5.69	2.32	10.62	4.57	11.17	4.30	2.23	6.28
3	8.31	11.65	5.69	2.30	10.70	4.16	11.27	4.39	2.29	6.40
4	10.51	11.06	5.76	2.18	11.55	3.93	11.65	4.47	2.39	6.34
5	9.13	11.40	5.73	2.42	10.31	13.18	11.50	3.79	1.34	8.14
6	8.43	11.40	5.75	2.43	10.31	5.77	11.96	4.48	2.39	6.36
7	10.99	11.48	5.39	2.03	10.87	5.41	11.85	4.64	2.45	6.67
8	10.75	11.50	5.69	2.05	11.97	5.13	11.69	4.78	2.47	7.01
9	10.66	11.45	5.90	2.05	12.93	18.32	11.40	3.95	0.97	12.24
10	12.00	11.17	5.87	2.35	11.11	9.63	11.21	5.00	1.83	10.40
11	11.96	11.20	6.17	2.37	12.19	8.97	11.30	5.29	1.97	10.80
12	11.94	11.20	6.43	2.39	13.18	8.80	11.30	5.54	2.09	11.15

Guided Mode SPP effective index