Enhanced mid-infrared absorption by Fabry-Pérot cavity resonance of the coupled surface plasmon and phonon polaritons

Satya R. Kachiraju[1], Ivan Nekrashevich[3,4], Imtiaz Ahmad[1], Hira Farooq[1], Long Chang[3], Sangsik Kim[2] and Myoung-Hwan Kim[1]

[1]Department of Physics and Astronomy, Texas Tech University, Lubbock, TX 79409, USA., [2]Department of ECE, Texas Tech University, Lubbock, TX 79409, USA.
[3]Department of Integrated Bio & Nano Systems, University of Houston, Houston, TX 77204, USA. [4]Los Alamos National Laboratory, Los Alasmos, NM 87545, USA.

TEXAS TECH UNIVERSITY

ABSTRACT

Resonant optical cavity has been utilized extensively in plasmonic nanostructure to enhance a coupling of light and the sub-wavelength scale resonator. The enhanced optical power absorption has been observed in various types of Fabry-Pérot resonant cavity constructed in metal-insulator-metal plasmonic waveguides. For long-wave infrared, surface phonon polaritons have been considered as an alternative to surface plasmon polaritons because of low optical power loss. However, Fabry-Pérot cavity has not been adapted yet because of the complexity to make polar dielectric waveguide which requires both strong field confinement and long propagation length. Here, we experimentally demonstrate the resonant cavity in asymmetric metal-insulator-polar dielectric waveguides presenting a strongly enhanced optical power absorption from the frequency tunable cavity mode of the coupled surface plasmon-phonon polaritons. Our resonant cavity will benefit to design devices for infrared control of fundamental optical processes at the sub-wavelength nanoscale.

INTRODUCTION

Metasurfaces:

- 2D designer optical structures that introduce spatially varying optical properties.
- They are optically thin,
- subwavelength resolution
- Metasurfaces for **free space wave control**
- Metasurfaces for **confined wave control**

Do metasurface control surface waves?

New Metasurface building blocks

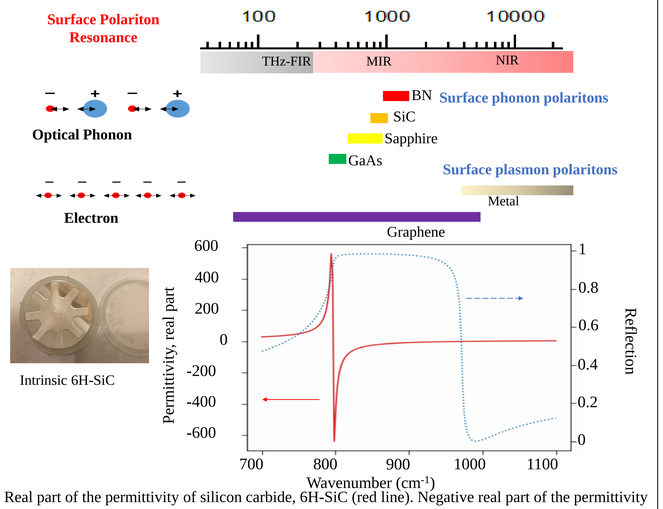
Polar optical phonon resonance in ionic crystals

❑Negative permittivity like metal

- high coupling efficiency with light
- Surface is highly reflective.

❑No free charge carriers

- Low optical loss
- Surface phonon polaritons are active like surface plasmons.



Real part of the permittivity of silicon carbide, 6H-SiC (red line). Negative real part of the permittivity in optical phonon band between which are 797 cm^{-1} and 972 cm^{-1} results in the highly reflective surface (blue dotted line).

Device Design and Fabrication

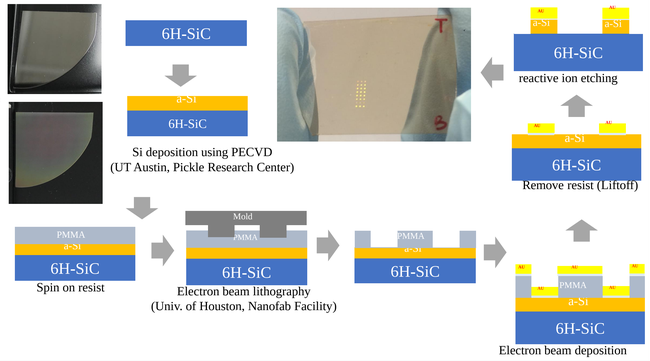
Device Design

- We adapted a design of metal-dielectric-polar dielectric structure supports a propagating coupled surface plasmon polariton (SPP)-surface phonon polariton (SPhP) mode, when the polar dielectric has negative real permittivity at Reststrahlen band.
- we experimentally demonstrate asymmetric metal-insulator-polar dielectric waveguides with sub-wavelength grating structure for surface phonon polaritons showing a strongly enhanced optical power absorption by Fabry-Pérot cavity resonance of the propagating coupled mode of surface plasmon polaritons and surface phonon polaritons.

Device Fabrication

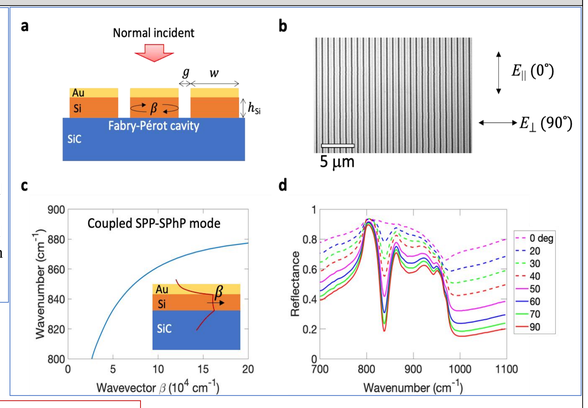
40 nm Gold and 80 nm amorphous silicon multiplayer was created by e-beam metal deposition and plasma Enhanced chemical vapor deposition, respectively. The pattern was fabricated by e-beam lithography, nanoimprint, and reactive ion etching. The devices have different cavity width w from 800 nm to 500 nm with the same period of 900 nm.

Device Fabrication steps



RESULTS

Fig. 1 a Schematic of device and Fabry-Pérot cavity. **b** Scanning electron microscope (SEM) image of the fabricated device. **c** Dispersion relation of the coupled SPP-SPhP mode given by analytical calculation when h_{Si} = 80 nm. Inset: evanescent magnetic field profile (pointing inside the page) of the transverse magnetic coupled mode over the layers (vertical axis). The propagation constant β (horizontal axis) ~ 4×10^4 cm^{-1} for the cavity width w = 800 nm to get $\beta \cdot w \approx \pi$ rad results in resonance frequency around 820 cm^{-1}. **d** Measured mid-infrared reflection spectrum of the device with respect to the polarization of the light under normal incidence. The strong and well-defined absorption shows at a frequency of 838 cm^{-1} which is close to the value obtained by Fabry-Pérot cavity resonance of the coupled SPP-SPhP mode.



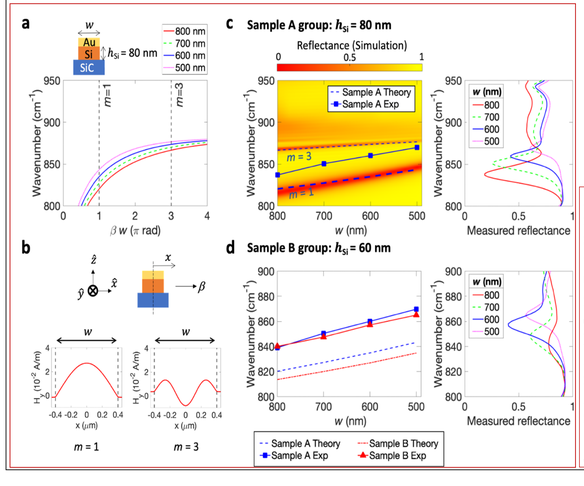


Fig. 2 Spectral tunability of the coupled SPP-SPhP cavity resonance. **a** Fabry-Pérot resonance condition of the coupled SPP-SPhP modes with respect to four different cavity lengths w when silicon thickness h_{Si} = 80 nm. **b** Standing waves of the transverse magnetic field H_y obtained by full-wave simulation in the cavity length w = 800 nm at two resonance frequencies of 815.8 cm^{-1} when m = 1 and 867.7 cm^{-1} when m = 3. **c** Measured and simulated reflectance of sample A group which has h_{Si} = 80 nm. Left: Contour plot shows reflectance given by full-wave simulation with respect to frequency and cavity length. Right: Measured reflectance of sample A group. **d** Sample B group which has h_{Si} = 60 nm. Left: Dot-dashed red line indicates m = 1 resonances of sample B obtained analytically comparing with m = 1 resonances of sample A.

RESULTS

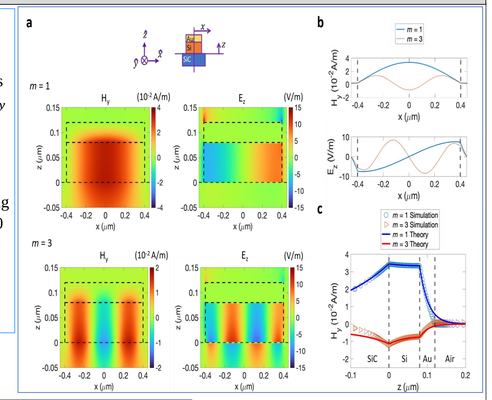


Fig. 3 a (top) Schematic of the simulated geometry. The coupled SPP-SPhP mode propagates along x-axis with the propagating constant β, which is associated with two fields of H_y and E_z. (middle) Field distribution of H_y and E_z inside the cavity at the half wave resonance condition (m = 1). (bottom) Field distribution of H_y and E_z inside the cavity at the 1.5 wave resonance condition (m = 3). **b** The simulated field profiles of H_y and E_z along x-axis in the middle of the silicon layer (z = 40 nm) at two resonance conditions (m = 1 and m = 3). **c** The calculated (symbol) and simulated (line) field profiles of H_y along z-axis at the center of the cavity for two resonance conditions.

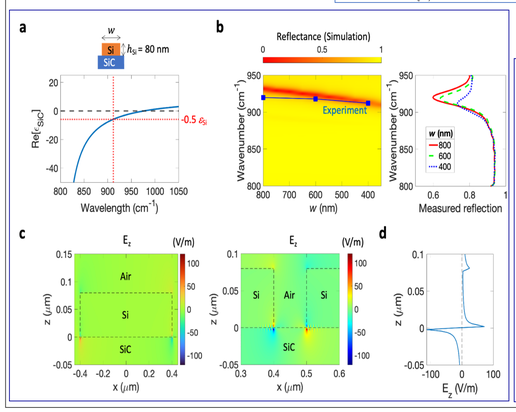


Fig. 4 Localized surface phonon polaritons. **a** Real part of 6H-SiC permittivity ε_{SiC} with respect to a frequency of light. Fröhlich void resonance condition for a dipole of localized SPhP can be determined when $\mathrm{Re}[\varepsilon_{SiC}] = -0.5\varepsilon_{Si}$. **b** Measured and simulated reflectance with respect to the cavity length w (or air gap between two cavities). **c** Electric field E_z distribution of the localized SPhPs. (Left) The electric field is highly localized only at the edge of Si and SiC boundary. (Right) Opposite polarized field distribution indicates dipole charges at the edge boundary. **d** Electric field E_z profiles along z-axis at the cavity boundary.

CONCLUSIONS

- Experimentally demonstrates the resonant optical cavity for the coupled mode of surface plasmon and phonon polaritons confined in deeply sub-wavelength thin metal-dielectric aperture on polar dielectrics.
- Enhanced mid-infrared absorption up to 80% is observed at half-wave Fabry-Pérot cavity resonance under normal incident polarized light.
- The resonance frequency is tuned broadly with respect to the cavity width.
- Although the top metallic layer reduces the propagation length of the mode significantly, the higher field confinement is the trade-off to allow the coupled mode trapped in the cavity. Such deeply sub-wavelength thin polaritonic resonant cavity will benefit to long-wave infrared control of fundamental optical processes including absorption, modulation, and emission as well as spatial control of the light using phase-gradient metasurfaces, thermal metasurfaces, and topological photonic devices.

BIBLIOGRAPHY

[1]Maier, S. A. Plasmonics: fundamentals and applications. Berlin: Springer. (2007)
[2] Moreau, A., Ciracì, C., Mock, J. et al. Controlled-reflectance surfaces with film-coupled colloidal nanoantennas. *Nature* 492, 86–89 (2012). https://doi.org/10.1038/nature11615
[3]Caldwell, J. D., Lindsay, L., Giannini, V., Vurgaftman, I., Reinecke, T., Maier, S. & Glembocki, O. Low-loss, infrared and terahertz nanophotonics using surface phonon polaritons. *Nanophotonics*, 4(1), 44-68 (2015). https://doi.org/10.1515/nanoph-2014-0003
[4] [JC2] Caldwell, J. D., Glembocki, O. J., Francescato, Y., Sharac, N., Giannini, V., Bezares, F. J., Long, J. P., Owrutsky, J. C., Vurgaftman, I., Tischler, J. G., Wheeler, V. D., Bassim, N. D., Shirey, L. M., Kasica, R. & Maier, S. A. Low-Loss, Extreme Subdiffraction Photon Confinement via Silicon Carbide Localized Surface Phonon Polariton Resonators. *Nano Letters* 13 (8), 3690-3697 (2013). DOI: 10.1021/nl401590g
[5] [AH1] Huber, A., Ocelic, N., Kazantsev, D. & Hillenbrand, R. Near-field imaging of mid-infrared surface phonon polariton propagation. *Appl. Phys. Lett.* 87, 081103 (2005).