Planar Resonators Supporting Extremely Confined Phonon-Polariton Modes

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Abstract: Infrared nanoimaging revealed extremely subwavelength sheet and edge surface phonon-polariton modes on few-nm thick CMOS-compatible Ge-on-SiC resonators. Surface nature of phononic modes on these ultrathin planar structures enables local sensing at the molecular scale. © 2020 The Authors

Plasmonics on metal-dielectric interfaces was widely seen as the main route for miniaturization of components and interconnect of photonic circuits. However recently ultra-confined surface phonon-polaritonics in high-index chalcogenide films of nanometric thickness have emerged as important alternative for plasmonics. Here, using scanning near-field imaging we demonstrate surface phonon-polaritons in nanometric films of CMOS-compatible germanium on silicon carbide. We show that Ge@SiC resonators with sub-micron-size footprint can support sheet and edge standing modes excited at the free space wavelength hundred times larger than the physical dimensions of the resonators. Such deeply subwavelength resonators are of interest for highly-density optoelectronic applications, filters, dispersion control and optical delay devices.

The experimental samples is based on few-nm thick Ge@SiC interfaces (Fig. 1h,i), which represent a deeply subwavelength photonic system at the used mid-IR excitation laser frequency. Owing to its excellent adhesion and exceptional infrared properties, germanium film enables low-loss ultrasmooth interfaces, which provide excellent conditions for support of high-quality mid-IR SPhP modes. Examples of the scattering-type scanning near-field

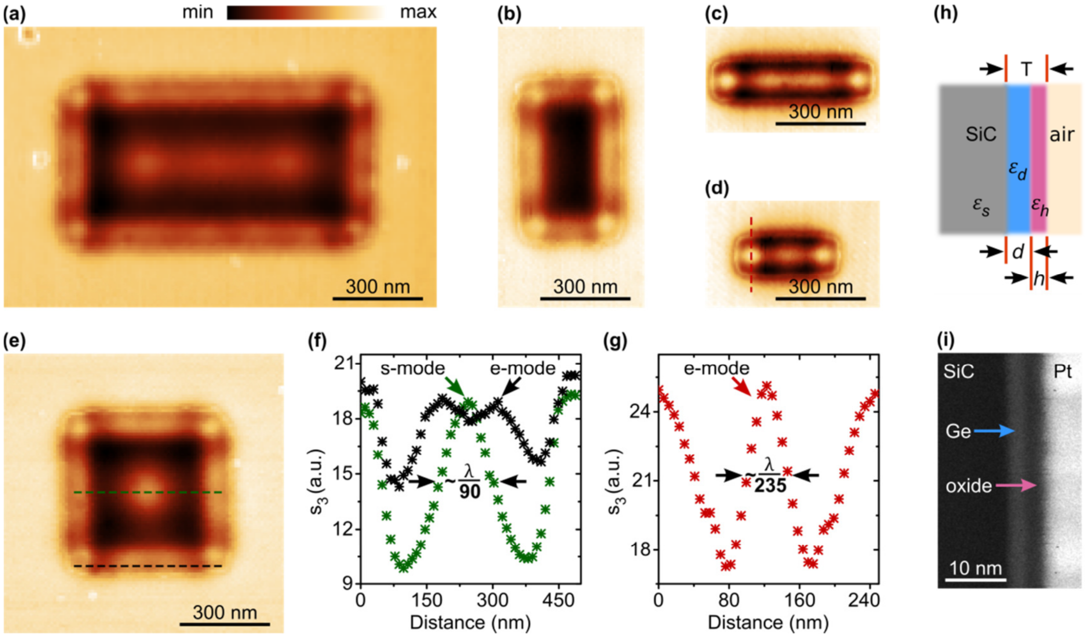

Fig. 1. Highly-confined surface polariton modes on 7-nm thick Ge@SiC nanoresonators. (a-e) Near-field images (scattering amplitude s_3) recorded at ω = 924.5 cm^{-1} for 1000x500, 300x500, 500x100, 300x100 and 500x500 nm structures respectively. (f, g) Cross-sections along dashed lines in images (d) and (e), denoted with corresponding colors; λ denotes the wavelength of the free-space laser radiation used in the experiment. (h) Schematics of the sample cross-section: four-layer system consisted of bulk SiC substrate, nanometric germanium and oxide layers (combined thickness T ~ 7 nm), and air. (i) Dark-field STEM image of germanium film vertical cross-section, which consists of (from left to right) SiC substrate, Ge and oxide layers, and protective Pt cap; the image was recorded 16 days after the sample exposure to the ambient atmosphere; Ge film was protected by a Pt layer priory the cross-section milling.

optical microscopy (s-SNOM) images of various resonator modes are shown in Fig. 1a-e. At the same time, germanium also allows the formation of molecularly-thin oxidized layer (i.e. Ge oxide), which gives us the opportunity to trace polaritons dynamics under molecular-scale interactions of the system with the environment. Owing to the surface nature of the modes, the phonon-polaritons in such ultrathin planar structures feature ultra-high sensitivity, which enables detection of the interface composition change at the molecular scale.

In the s-SNOM experiment, the laser radiation within the reststrahlen band of SiC excites SPhPs by means of sub-diffraction optical antenna (metallized tip) for simultaneous launching and detection of polaritonic waves. These waves undergo reflections from the edges of Ge structures forming interference patterns, which are mapped together with the topography upon scanning the sample. The observed near-field distributions on nanoresonators of different sizes show deep sub-diffraction optical features, represented by number of hot spots both at the inner part of resonators and at its edges. Such spatial features are usually classified as sheet (s-) and edge (e-) modes correspondingly. Figure 1f,g show optical cross-sections taken along dashed lines across near-field images (Fig. 1d,e) of the 500x500 nm square and a 100x300 nm rod resonators. Estimates for the spatial confinement of the sheet mode at the center of the square resonator and the edge mode at the corner of the rod resonator are 90 and 235, respectively (defined as the excitation laser wavelength divided by the full width of the observed field distribution peaks at its half maximum). Such a large squeezing of light via SPhPs could enable on-chip optoelectronic devices with ultracompact footprints at the subwavelength scale. Furthermore, we observe tighter spacing of the peaks distribution along the edge compared to the inner part of the resonator sheet (Fig. 1f), which implies the higher-momentum nature of edge modes. The higher confinement of edge modes has been observed in plasmonic and hyperbolic material systems, while our results provide the first observation of the phenomenon in nearly isotropic media supporting surface phonon-polaritons.

We further demonstrate that tuning of near-field patterns in the resonator is possible by changing both the composition of the material and the laser excitation frequency. Importantly, we revealed that a complete switching (from a lower to a higher order) of the observed mode is possible by sub-nm (i.e. molecular-scale) change in the resonator composition, which demonstrates ultrasensitive properties of the Ge-on-Si polaritonic system at the bottom limit of chemical interactions. To explain these observations, we develop an analytical model that allows direct analysis of the dispersion and the polariton wavelength scaling in four-layer interface (consisted of SiC, Ge, oxide and air; see Fig. 1h) for the case of highly confined surface polaritons. This condition results in the following dispersion relation:

$$\alpha_1 e^{2k_p(h-d)} + \alpha_2 e^{2k_p h} + \alpha_3 e^{-2k_p d} \simeq \alpha_4 \qquad (1)$$

where k_p is the complex polariton wavevector, $\alpha_1(\omega) = (\varepsilon_h - \varepsilon_d)(1-\varepsilon_h)(\varepsilon_s + \varepsilon_d)$, $\alpha_2(\omega) = (\varepsilon_h + \varepsilon_d)(1-\varepsilon_h)(\varepsilon_d - \varepsilon_s)$, $\alpha_3(\omega) = (\varepsilon_h + \varepsilon_d)(1+\varepsilon_h)(\varepsilon_s + \varepsilon_d)$, $\alpha_4(\omega) = (\varepsilon_h - \varepsilon_d)(1+\varepsilon_h)(\varepsilon_s - \varepsilon_d)$ and ε_s, ε_d, ε_h are permittivities of the substrate (SiC), germanium and oxide layers, respectively. By measuring SPhP wavelength at different time after the sample oxidation we retrieve and trace the oxide thickness dynamic via equation (1). The oxidation of germanium film has been additionally cross-analysed using X-ray photoelectron spectroscopy and scanning transmission electron microscopy (STEM), which directly show the chemical presence of germanium oxide at the film surface and its developing with time to the thickness of 3.6 nm in agreement with the model prediction (Fig. 1i).

We experimentally show that switching of the both sheet and edge near-field patterns to the next order is possible by a very small (<0.5 %) shift of the excitation frequency, providing efficient spectral control of the resonator optical response. In addition, we discuss potential applications of Ge@SiC platform for building small-footprint mid-IR metamaterials.

In summary, we demonstrate for the first time that nanometric interfaces between germanium and silicon carbide are capable to support highly-confined mid-IR surface phonon-polariton modes at the nanoscale. Our research would be useful in designing low-loss and highly integrated phononic devices in the infrared part of the spectrum. Owing to the surface nature of the polaritons, the proposed architecture displays good performance at several nanometer semiconductor thicknesses, adding new opportunities for "flatland" optoelectronics. The concept can be potentially applied to number of technologically important semiconductor and dielectric compounds. The variety of deep sub-diffraction SPhP modes revealed in Ge-SiC nanoresonators shows feasibility of potential device footprint miniaturization. Considering high field confinement, SPhPs tunabilty and CMOS-compatibility, the proposed platform could provide a rich playground for on-chip photonics and sensing applications.