Mid-Infrared Plasmonic Platform Based on n-Doped Ge-on-Si: Molecular Sensing with Germanium Nano-Antennas on Si

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***Abstract*— CMOS-compatible, heavily-doped semiconductor films are very promising for applications in mid-infrared plasmonic devices because the real part of their dielectric function is negative and broadly tunable in this wavelength range. In this work we investigate n-type doped germanium epilayers grown on Si substrates. We design and realize Ge nano-antennas on Si substrates demonstrating the presence of localized plasmon resonances, and exploit them for molecular sensing in the mid-infrared.**

I. INTRODUCTION

The quest for novel plasmonic materials has been a lively area of research over the last few years [1]. In the mid-infrared (mid-IR) spectral region, in particular, localized plasmon resonances in nano-particles and nano-antennas hold promise for enhanced IR spectroscopies, with key applications in biology, medicine, and security. In this frame, the development of a CMOS-compatible plasmonic platform in the mid-IR could have disruptive effects for future technologies, allowing for integrated and cost-effective sensing devices.

II. RESULTS

Electron-doped germanium (n-Ge) epilayers, doped in the 10^{17}-10^{19} cm^{-3} range, are grown on silicon wafers by low energy plasma enhanced chemical vapor deposition. The approximately 500 nm thick Ge films are characterized by means of reflectance spectroscopy at room temperature between 50 and 5000 cm^{-1} with a Fourier Transform Infrared (FT-IR) spectrometer (Bruker IFS66v). A home-built optical setup based on parabolic mirrors and broadband beamsplitters is used to shine light on the sample surface (n-Ge side) and recollect the reflected intensity on the same optical path, so to ensure perfectly normal incidence conditions (Fig. 1A).

We demonstrate that the unscreened plasma frequency can be tuned up to 2000 cm^{-1}, by combining in-situ doping with post growth laser annealing. By resorting to multilayer Drude modelling (see Fig. 1B) and Kramers-Kronig approach [2], the optical constants and scattering times are calculated. The average electron scattering rate is dominated by scattering with optical phonons and charged impurities and increases almost linearly with frequency [3].

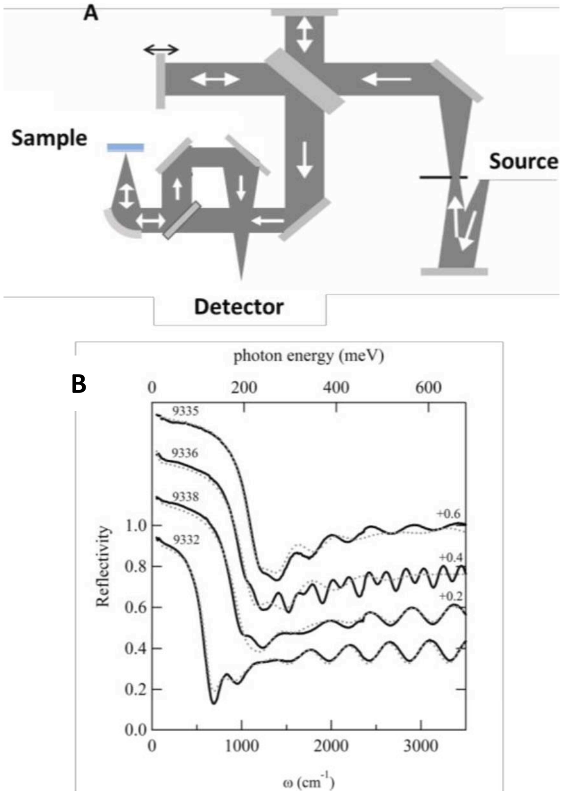

Fig. 1. A) Schematic drawing of the Michelson interferometer with home-built reflectance setup. B) Infrared reflectivity of n-Ge epilayers with different doping levels (solid lines) and multilayer Drude model (dotted lines).

We employ frequency- and time-domain simulations to design single- and double-arm plasmonic antennas in the form of 2.0 μm long, 0.8 μm wide and 1.0 μm thick blocks (Fig. 2). The simulations show the existence of two longitudinal antenna resonances (R1 and R2) with hotspots located at the Ge/Si and Ge/Air interface respectively. We investigate them by reflection/transmission spectroscopy, demonstrating the presence of the expected localized plasmon resonances in the mid-IR [4]. Experimental normal-incidence reflection and extinction spectra are in excellent agreement with simulated spectra as extensively reported in Ref. [4] and, for the material labeled “9338” in Fig. 1, one finds R1 around 500 cm^{-1} and R2 around 850 cm^{-1} [4].

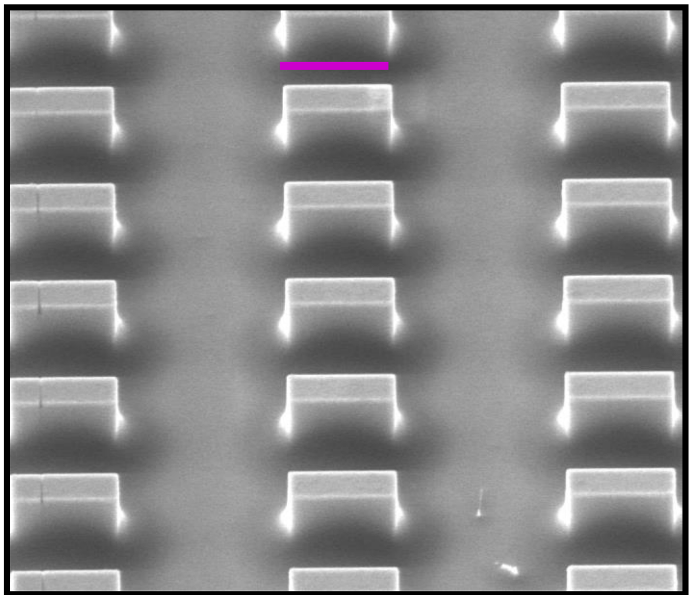

Fig. 2. A) A scanning electron microscope (SEM) image of an array of single-arm antennas coated with PDMS for the sensing demonstration (see text). The purple scale bar is 2 μm long.

We demonstrate the potential for plasmon-enhanced vibrational spectroscopy on Ge-on-Si substrates by sensing a thin elastomer layer with thickness of about 40 nm through one of its mid-IR vibrational lines, which was quasi-resonant with R2, employing both single-rod antennas and double-rod antennas with a gap.. To do so, we employ linearly polarized radiation in a FT-IR setup (Fig. 3A). We have coated the antennas with polydimethylsiloxane (PDMS) that displays a vibrational motion (Si-C cage motion) at 800 cm^{-1}. The PDMS layer conformally covers the antennas, apart from the bottom corner between the Ge block and the Si substrate in the case of gap antennas (see the sketch in Fig. 3A). In Fig. 3B we show the ratio between the spectra collected for parallel and perpendicular polarization (red and blue arrows respectively) for the clean antennas (dotted lines) and the PDMS-coated antennas (continuous lines). It is worth noticing that the vibrational feature at 800 cm^{-1} is not visible in the antennas realized on the nominally undoped material (bottom-right panel of Fig. 3B, labelled b4), while it is clearly observed for the different plasmonic antennas investigated (b1 to b3). This fact indicates the coupling between the vibrational resonances and the longitudinal plasmonic resonances. In Ref. [4] it was calculated an enhancement of two orders of magnitude in the vibrational fingerprint visibility was calculated, originating from the presence of PDMS in the R2 hot spots, i.e. the high field regions at the top corner of the of the n-Ge antennas.

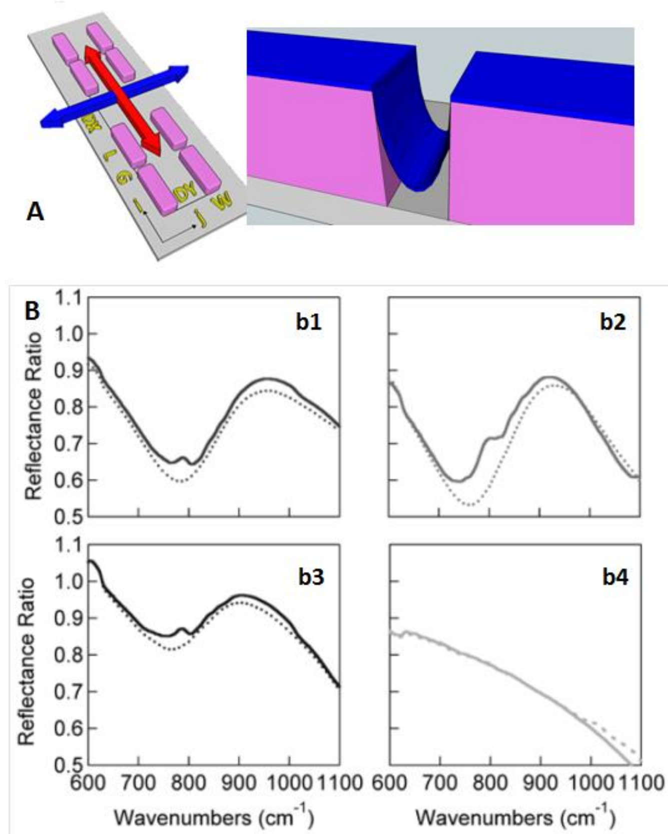

Fig. 3. A) A sketch of the antenna array and the electric field polarization (left) and a sketch of the PDMS layer that coats the antennas in a non-perfectly conformal way (right), B) ratio between the reflectivity with parallel polarization and with perpendicular polarization,.measured for the doped and undoped (bottom right panel, labelled b4) antenna arrays The ratio has been calculated for both the antenna arrays before deposition of PDMS (dotted) and antenna arrays covered with PDMS (solid lines).

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