Mid-infrared Plasmonic Antennas made of Electron-doped Epitaxial Germanium-on-Silicon

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***Abstract*— We are developing an all-semiconductor plasmonic platform for mid-infrared sensing which includes growth of epitaxial n-doped germanium films, spectroscopic test and electromagnetic design of plasmonic antennas.**

I. Introduction And Background

MID-INFRARED (mid-IR) sensors based on resonant absorption through specific vibrational excitations in molecules may become a fundamental tool for biology, chemistry, medicine and safety&security, after the recent development of tunable mid-IR quantum cascade lasers. Plasmonics is the most promising approach to achieve deep sub-wavelength concentration of optical fields towards single-molecule sensing. At variance with radio-frequency antennas treated in the perfect-electric-conductor limit, plasmonic antennas produce intense localized energy spots at electromagnetic frequencies close to the plasma frequency ω_p of the conductor they are made of[1].

So far, plasmonic antennas have been based on metals such as gold, silver, or aluminum, which display ω_p in the visibleand UV range. A material for plasmonic antennas at mid-IR frequencies should have electron densities in the 10^{19} - 10^{20} cm^{-3} range. In this work, we show that ω_p at arbitrary values in the mid-IR can be obtained in germanium with high donor density (n^+-Ge), in conjunction with its small conductivity effective mass $m^* = 0.12\ m_e$, according to the formula:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{\varepsilon_0 \varepsilon_\infty m^*}} \qquad (1)$$

Here, n_e is the density of activated carriers, which can be optimized during the epitaxial material growth., The n^+-Ge material used in this work is epitaxially grown on silicon substrates in ultra-high vacuum by plasma-enhanced chemical vapor deposition and co-doping by PH_3 gas. Such epitaxial plasmonic material features a limited surface roughness, (RMS below 1 nm) which is one of the limiting factors of plasmon resonance linewidth, it can be tuned by an external electric gate potential, and it is compatible with mainstream silicon foundry technology, enabling low-cost integrated plasmonic chips for sensing applications [2].

II. Results

We have measured the absolute mid-IR reflectivity of 1 micron-thick n^+-Ge films on Si substrates with different donor densities N_d by Fourier-transform spectroscopy. Screened plasma frequencies up to 1050 cm^{-1} have been found. By comparing the mid-IR results with the DC transport data, we found that Eq. 1 is verified, leaving room for further improvement of dopant incorporation and activation.

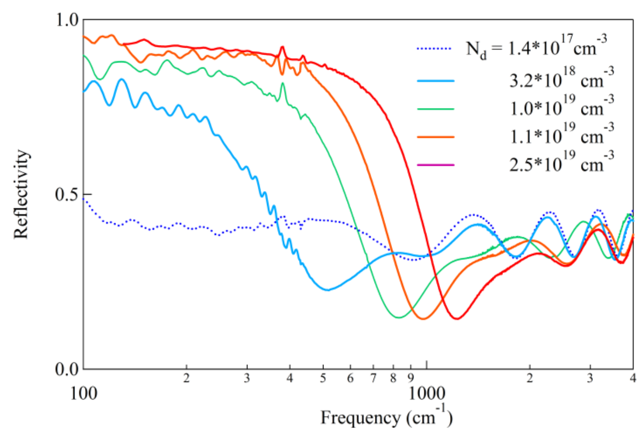

Figure 1. Reflectivity spectra of n^+-Ge-on-Si thin films. The dielectric constant extracted from the reflectivity data is used as input for electromagnetic design of mid-IR plasmonic antennas.

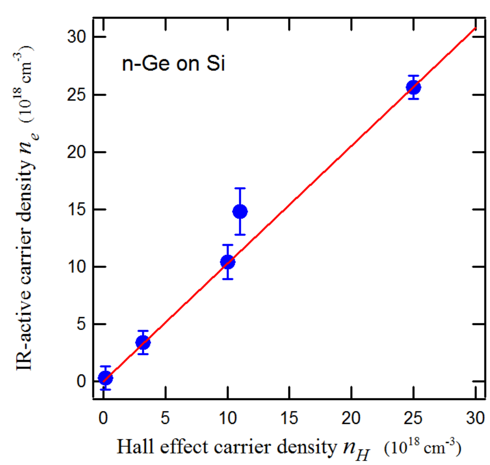

Figure 2. Carrier density as determined from IR measurements vs. carrier density obtained by Hall-effect measurements. The red line represents the identity $n_e = n_H$

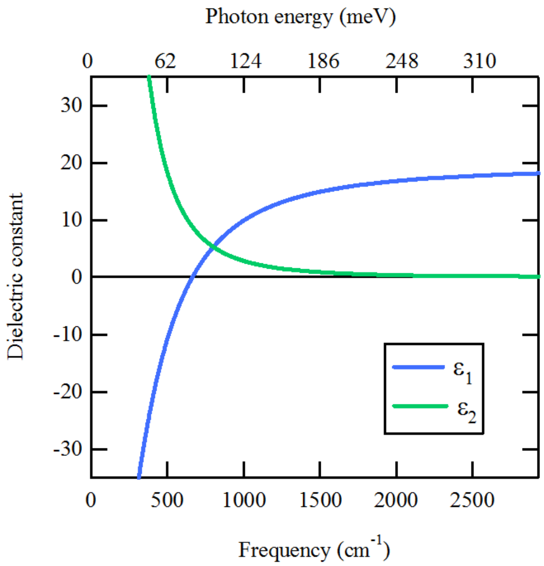

Figure 3. Dielectric function of the n-doped Germanium film as determined from the analysis of the raw data shown in Fig. 1.

The reflectivity spectra have been modeled with a Drude-Lorentz multi-oscillator model and the scattering rate is found to be independent on N_d , at least below N_d = 10^{19} cm^{-3} indicating that electron-phonon scattering is the main contribution to the Drude damping.

The main advantages of doped Germanium over doped Silicon to realize mid-IR antennas are: (i) the smaller conductivity effective mass (m^* = 0.12 for Ge, while m^*= 0.26 for Si) that provides a higher plasma frequency for the same amount of doping; (ii) a slightly higher refractive index (4.0 vs. 3.4) that allows to confine light in dielectric structures with suitable geometries; (iii) a lower ionization energy of shallow donors which may lead to higher ultimate doping levels. Indeed, the material science effort at the moment is to find strategies to increase the donor concentration N_d, while keeping high the dopant activation ratio n_e / N_d. In Fig. 2 we compare the activated carrier density n_e as obtained from the squared mid-IR plasma frequency (see Eq. 1) to the carrier concentration obtained by Hall effect measurements n_H. One can see that the dopant activation is close to 100% for our material up to N_d = 2.5 10^{19} cm^{-3} .

The complex dielectric function $\varepsilon(\omega)$ reconstructed from the Drude-Lorentz model is shown in Fig. 3. Note that the zero-crossing point of the real part $\varepsilon_1(\omega)$, which is closely related to the screened plasma frequency of Eq. (1), falls in the mid-IR range as expected. The functions in Fig. 3 were used as input for the electromagnetic design of mid-IR antennas by using a finite-difference time-domain simulation code. In particular, plasmonic antennas with operation frequency close to the screened plasma frequency were designed, with the aim of investigating the plasmonic regime in the absence of significant interband absorption, which is always present in metallic nanoantennas at visible frequency. The results of parametric simulations (not shown) is that electric field enhancements of the order of 30 are expected for specific wavelengths and designs. In Figure 4a, we show the electromagnetic design of a n-Ge dipole antenna on Si, where the dimensions are scaled to resonate at 1000 cm^{-1} . The corresponding fabricated antenna is shown in Figure 4b. One can see that fabrication constraints do not limit the accuracy required by the design. Spectroscopic tests are ongoing.

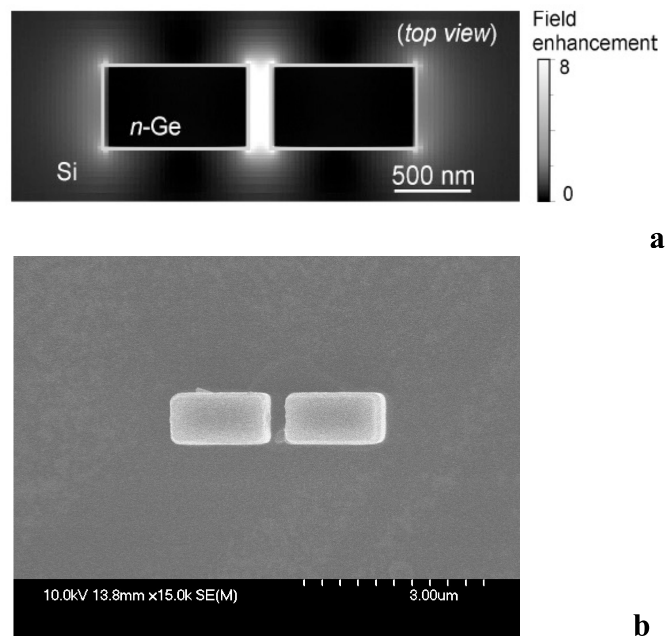

Figure 4. (a) Electromagnetic design of mid-IR plasmonic dipole antenna with electric field map. (b) Scanning electron micrograph of the antenna made of n-doped Germanium hetero-epitaxially grown on a silicon substrate.

References

[1] Paolo Biagioni, Jer-Shing Huang and Bert Hecht "Nanoantennas for visible and infrared radiation" Rep. Prog. Phys. 75, 024402 (2012).

[2] R. Soref "Mid-infrared photonics in silicon and germanium" Nature Photonics 4, 495 (2010).