Heavily-Doped Germanium on Silicon with Activated Doping Exceeding 10^{20} cm^{-3} as an Alternative to Gold for Mid-Infrared Plasmonics

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Abstract – **Ge-on-Si has been demonstrated as a platform for Si foundry compatible plasmonics. We use laser thermal annealing to demonstrate activated doping levels >10^{20} cm^{-3} which allows most of the 3 to 20 µm mid-infrared sensing window to be covered with enhancements comparable to gold plasmonics.**

I. Introduction

Recently heavily doped semiconductors have been investigated as a promising way to obtain tunable plasmonic materials in the mid-infrared (mid-IR) [1][2]. The plasma frequency of a semiconductor depends on the carrier density n_e according to the relation $\omega_p \propto \sqrt{n_e/m^*}$, where m^* is the effective mass of the free carriers involved in the plasma oscillation. Among the semiconductors considered for mid-IR plasmonics, the compatibility of Ge with standard Si foundry processes makes it an attractive plasmonic material [3][4]. In order to cover the whole relevant fingerprint region in the mid-infrared (6.7 µm to 20 µm wavelength) and the gas sensing window (3 µm to 5 µm), it would be desirable to obtain Ge epilayers with a doping density > 10^{20} cm^{-3} over a uniform doping profile greater than a few electromagnetic skin depths, i.e. 250-500 nm. Therefore, plasmonic devices require significantly thicker epilayers with uniform doping compared to Ohmic contacts for advanced CMOS or bipolar processes. The active doping in phosphorous doped Ge is usually limited to 2-5 × 10^{19} cm^{-3} because the dopants form neutral complexes with the vacancies present in the material. In this work, we investigate laser thermal annealing (LTA) performed on in-situ doped Ge-on-Si epilayers to deliver the high activated doping densities required for plasmonic applications.

II. Sample growth and processing

The sample was grown by Low-Energy Plasma-Enhanced Chemical Vapour Deposition (LEPECVD) [5] on (001) Si substrates. The Ge epilayer consists of a ~ 600 nm thick layer deposited at 450 °C at a rate of 1 nm/s with a GeH_4 flux of 20 standard cubic centimetres per minute (sccm). The doping was obtained by adding 0.35 sccm of PH_3 during the deposition. After the growth, the sample was treated by LTA using a XeCl laser equipped with a beam homogenizer (λ = 308 nm, 160 ns pulse duration).

III. Characterization

The incorporated and the activated doping density have been measured by secondary ion mass spectrometry (SIMS) and infrared reflectometry respectively. Infrared reflectometry was performed in the full range from the far-IR to the near-IR to determine the optical properties of the sample before and after the LTA treatment. The frequency dependent absolute IR reflectivity R(ω) was measured in the 500 < ω < 5000 cm^{-1} (20 µm to 2 µm) range with a Fourier transform infrared (FTIR) spectrometer (Bruker IFS66v) equipped with cryogenic detectors: a 77 K HgCdTe photoconductor and a 4 K silicon bolometer. The active doping density is extracted by fitting the absolute infrared reflectance of the film with a multi-layer Drude model. The as-grown sample has an incorporated doping density of ≈ 1.7 × 10^{20} cm^{-3}

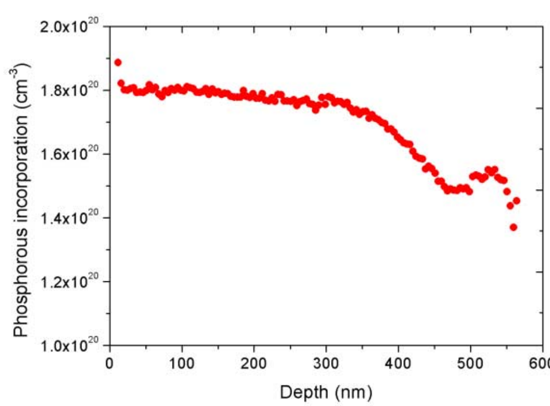

Fig. 1: The incorporated doping measured by SIMS in the as grown material.

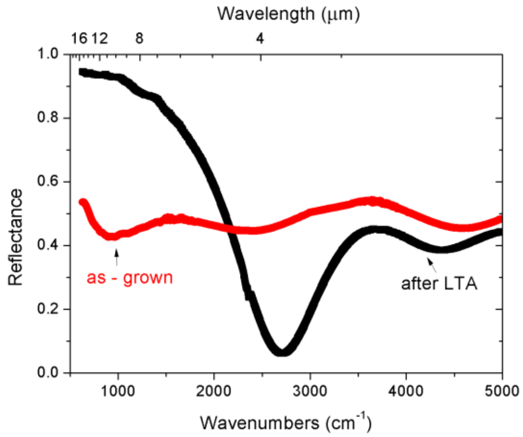

Fig. 2: The infrared reflectance of the Ge-on-Si epilayer before (red circles) and after (black squares) the LTA process. The as grown sample has an active doping density of 2.3×10^{19} cm^{-3} and the plasma frequency is located at ~ 1000 cm^{-1} (10 μm wavelength). The sample treated with the LTA has an active doping density of 1.3×10^{20} cm^{-3} and a plasma frequency of ~ 2700 cm^{-1} (3.7 μm wavelength).

while the activated doping density is limited to 2.5×10^{19} cm^{-3} (see Fig. 1 and Fig. 2). After the LTA process, the plasma edge of the material shifts toward higher frequencies (i.e. higher active doping densities, see Fig. 2). For a LTA energy density of 1.9 J/cm^2 the material has a plasma frequency located at about 2700 cm^{-1} (~3.7 μm wavelength), which corresponds to an active doping level of 1.3×10^{20} cm^{-3}.

IV. Plasmonic performance

To benchmark the new Ge-on-Si material platform against standard Au devices for mid-IR plasmonic sensing, we perform a systematic investigation using full electrodynamic calculations based on the finite element method and on the experimentally extracted dielectric constants. We optimize a resonant array of plasmonic slits and demonstrate that heavily-doped Ge, although not outperforming Au, guarantees a similar local field enhancement and accordingly the same order of magnitude in the surface enhancement of infrared absorption and scattering for the sensing of molecules (see Fig. 3 for a representative example).

V. Conclusions

To summarize, we have investigated the potential of the combined use of in-situ doping and post-growth LTA treatment to achieve extremely high levels of activated doping in Ge-on-Si epilayers. An activated doping density of 1.3×10^{20} cm^{-3} (which corresponds to a plasma wavelength of ~3.7 μm) has been demonstrated by infrared spectroscopy. Our work enables for the first time, the possibility to develop a mid-IR plasmonic platform exclusively relying on group-IV materials with sensing performance similar to the well-established designs

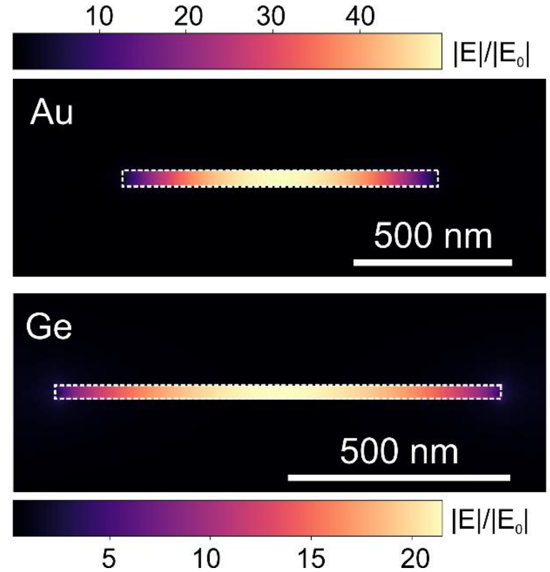

Fig. 3: Comparison of the local field enhancements for Au and Ge slits resonant in the mid-infrared.

based on Au and Ag [2]. These results enable a new class of n-Ge plasmonic sensors operating throughout the whole of the mid-infrared spectral fingerprint window and also part of the 3 to 5 μm wavelength gas molecular absorption window.

Acknowledgements

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