Excitation and Modulation of Surface Plasmon Polaritons at PN++ Junctions

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Abstract

We present excitation and active modulation of Surface Plasmon Polaritons (SPPs) at degenerately doped PN++-junction based on lattice matched Indium Gallium Arsenide. The device is experimentally characterized, showing far-field voltage assisted reflectivity modulation for mid-IR wavelengths. Numerical simulations of the device have confirmed the experimental findings and predict data rates of up to 1Gbits/s. Decreeing the device physical dimensions can lead to data rates in excess of 50Gbits/s, thus providing a new pathway toward fast plasmotronic devices.

1. Introduction

Photonics and in particular plasmonics has been recognized as a key technology for fast data communication and computing [1-3]. In this work we present an optoelectronic switch for functional plasmonic circuits based on active control of Surface Plasmon Polaritons (SPPs). The device, which we refer to as Surface Plasmon Polariton Diode (SPPD), consists of a degenerate PN++ semiconductor junction with an active drift-diffusion region formed between two control electrodes (see Fig. 1). Under forward bias minority carriers (electrons) are injected in the P- doped layer and for applied voltage higher than a critical value Vc the P-layer acquires a metal like characteristics impeding the propagation of the SPP across the active region and establishing the OFF state of the device. The lattice matched Indium Gallium Arsenide ($In_{0.53}Ga_{0.47}As$) is identified as the best semiconductor material for the practical implementation of the optoelectronic switch providing high optical confinement, reduced system size and fast operation. A steady-state SPP signal modulation higher than -20dB is predicted, and responsivities in excess of -1000 dB/V for Si and -500 dB/V are expected for applied bias close to a critical values Vc=1.14V for Si and Vc=0.81V for $In_{0.53}Ga_{0.47}As$. The numerical results show a well-defined distinction between the OFF and ON response times, with the former being substantially faster. Consistently, a faster response is observed for the In0.53Ga0.47As device with 3dB data rates in excess of 50Gbit/s. A proof of concept experimental study has been performed to assess the main switching mechanism behind the SPPD operation. Degenerate p-n++ junctions are grown epitaxially on InP and fabricated by spin-doping on Si-on-insulator (SOI) wafers. The devices are characterize both electrically and optically as a function of applied forward bias, with the measured change in reflectivity compared to the theory, see Figure 1.

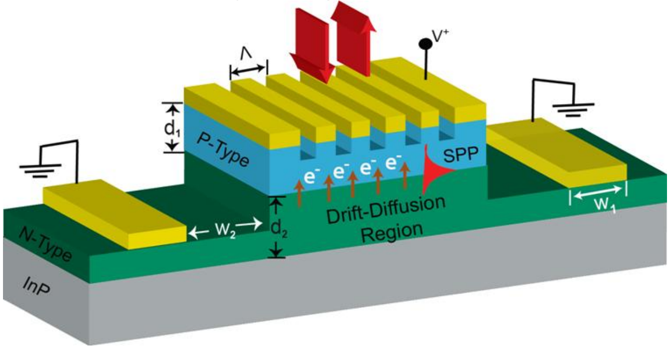

Figure 1: Schematic of the Surface Plasmon Polariton Diode (SPPD). The device consists of a lattice matched Indium Gallium Arsenide PN++-junction grown epitaxially on Indium Phosphide (InP) substrate. A grading with period Λ=2.4 μm is used to couple far-IR incident light to the SPP modes propagating the junction interface.

2. Device characterization

The SPPD device fabrication involves standard UV lithography, dry-etching, and metal deposition. A degenerately doped PN++- junction was grown by molecular beam epitaxy with doping concentrations N_A=1×10^18 [1/cm^3] and N_D=3.4×10^19 [1/cm^3]. Upon fabrication, the SPPD is characterized through polarization-dependent reflectivity measurements using a Bruker v80V Fourier transform infrared (FTIR) spectrometer working in fast-scan mode and normalized to reflection of a gold surface. Figure 2a shows the TE and TM polarization reflectivity spectra of the unbiased device obtained experimentally and compared to the theory. The reflectivity spectra for the TM polarized light shows distinctive dips at λ~6.7μm and λ~11.4μm, whereas for TE polarized light a dip in reflectivity is observed at λ~8.2μm. The observed dip in the TM reflectivity at λ~11.4μm is attributed due to excitation of a SPP at the junction interface, while the dips in the TM reflectivity at λ~6.7μm and TE reflectivity at λ~8.2μm correspond to Fabry-Perot resonances in the dielectric P- layer. As expected, only in the case of TM polarization do we observe an SPP mode propagating at the PN++- junction. To the best of our knowledge this result is the first experimental demonstration of SPPs at doped semiconductor junctions.

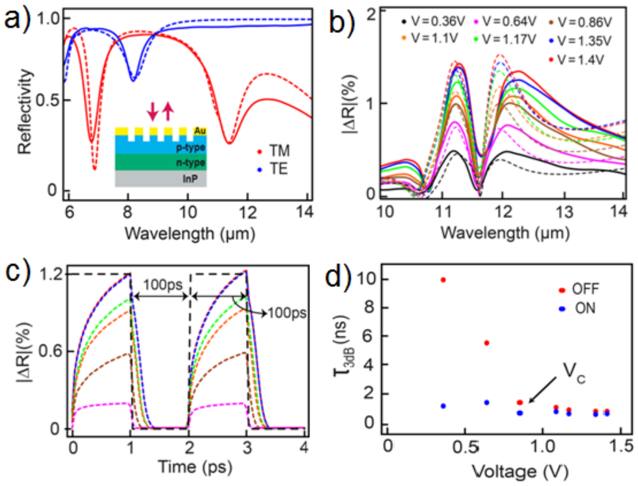

Figure 2: (a) Transverse magnetic (TM) and transverse electric (TE) polarized reflectivity spectra of the SPPD grating device (see insert) under zero bias. (b) The absolute change in reflectivity is experimentally obtained under various forward bias voltages (solid lines) and compared to the self-consistent electro-optic simulations (dashed lines). (c) Far field reflectivity (dashed lines) under step-type of input voltage (dashed black line) with various maximum forward bias voltages. SPPD 3dB response times as function of the applied external bias. In the calculations the operation wavelength is set at $\lambda=12\mu m$.

To assess the SPPD signal modulation, we have performed reflectivity studies under applied forward voltage bias. The numerical (dashed line) and experimental (solid lines) results are depicted in Figure 2b where we plot the absolute change in reflectivity $|\Delta R(\lambda,V)|=|R(\lambda,V)-R(\lambda,0)|$ for a set of forward voltages. As the external forward bias is increased, a far-field reflectivity modulation with respect to the unbiased device is observed. This behavior is consistent with expectations and is revealed both in the experimental data and numerical results. In our earlier theoretical studies [3] we have shown that semiconductor based Surface Plasmon Polariton Diodes (SPPDs) can provide excellent switching rates. To assess the response times of the experimental device, we have used the already validated self-consistent electro-optic model and performed a transient analysis under the input voltage biases used in the reflectivity studies (see Figure 2c). As the SPPD is forward biased, the far-field reflectivity is modulated corresponding to SPP switching OFF. The modulation of the signal increases with increasing bias. A well-defined distinction between the OFF and ON times is observed, with the latter being substantially faster. This distinction can be attributed to the different physical mechanisms that are involved when the device is under forward and zero bias. Namely, the OFF times are governed predominantly by the time of flight of minority carriers (electrons) across the PN++ depletion region while the ON times are facilitated by charge diffusion and recombination in the quasi-neutral regions. The 3dB ON/OFF times as functions of the applied bias are shown is Figure 2d. Close inspection reveals that the OFF times are inversely proportional with the applied external bias for $V<Vc=0.87$ V, and saturate at ≈0.5ns for $V>Vc$. This is because the electron injection rate into the P-layer is proportional to the applied bias. The ON times are weakly dependent on the external bias since excess minority carriers in the P-layer are removed by the process of diffusion and charge recombination. Overall, our data shows that for moderate applied voltages ($V\sim Vc$), 3dB data rates in excess of 1Gbit/s can be achieved. Finally, it should be noted that further improvement in the switching rates and minimization of the power dissipation can be accomplished by reducing the size of the SPPD drift-diffusion region and varying the P and N++- layers doping concentrations while keeping the SPP operation frequency within the mid-IR spectral range. The potential for such speed up was already studied theoretically [3] where we have shown that optimal SPPD device architectures can provide data rates in excess of 50Gbits/s.

3. Conclusions

We have demonstrated excitation and modulation of Surface Plasmon Polaritons (SPPs) at degenerate semiconductor interfaces. The modulation of the SPP modes under the presence of an external forward bias was studied experimentally and compared to numerical simulations, validating the switching mechanism underlying the device operation. The observed SPP modulation is the result of minority carrier injection across the metallurgical junction. Based on the excellent match between theory and experiment, we have perform time-dependent numerical studied of the SPPD response times under step-type of input bias. Our results show that the current device can support data rates of up to 1Gbit/s, which can be further improved for optimized geometries. Overall, the presented results indicate that SPP modes on degenerate semiconductor junctions can be utilized as signal carriers, an important step toward realization of fast optoelectronic circuit elements.

Acknowledgements

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