All-Plasmonic Thermo-Optic Modulator For GHz Signal Switching At The Metal-Semiconductor Interface

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Abstract

The integration of plasmonic components into optoelectronic platforms enables promising pathways for high-speed, ultra-compact signal modulation at the nanoscale. In this work, we present a novel all-plasmonic modulator, which leverages localized surface plasmon resonance (LSPR)-induced heating to dynamically modulate surface plasmon polariton (SPP) propagation along a metal-semiconductor (M-S) interface. By exploiting strong thermo-optic effects arising from LSPR excitation, the TAPS device enables active, localized refractive index tuning in the semiconductor, thereby offering a robust mechanism for GHz-rate plasmonic signal routing, logic operations, and reconfigurable photonic circuitry.

To investigate the underlying operational principles of the device and to elucidate the unique thermo-electro-optic mechanisms enabling modulation of surface plasmon polaritons (SPPs) at the metal-semiconductor (M-S) junction, we developed a comprehensive thermo-electro-optical model using COMSOL Multiphysics. The model integrates multiple physics modules to capture the complex multiphysics interactions driving device behavior. The Electromagnetic Waves Module is employed to determine optimal plasmonic particle geometries, sizes, and materials capable of supporting localized surface plasmon resonance (LSPR) in the mid-infrared (MIR) spectral range. The resulting electromagnetic energy absorption is then coupled into the Heat Transfer Module, which calculates the heat dissipation at the plasmonic particle-semiconductor interface and estimates the local lattice temperature of the semiconductor. Subsequently, the Semiconductor Module is used to model the voltage- and temperature-dependent charge carrier dynamics in the M-S junction. Based on these dynamics, the temperature- and voltage-dependent complex permittivity of the semiconductor is computed to evaluate the corresponding refractive index modulation, which governs the dynamic tuning of SPP propagation. Using the developed multiphysics framework, we conducted extensive parametric studies on particle shape, size, material, excitation wavelength, incident power, and doping concentration to optimize the operation of the thermo-assisted plasmonic switch (TAPS). Both steady-state and transient analyses were performed to fully characterize device performance under various operating conditions.

The results obtained from the developed multiphysics model reveal a modulation depth exceeding −30 dB, a thermal responsivity greater than $-3\ dB \cdot K^{-1}$, and switching capabilities in the GHz regime. These findings underscore the potential of the proposed device as a compelling platform for seamless integration of electronic and photonic functionalities. In conclusion, COMSOL Multiphysics enabled a comprehensive investigation of the underlying thermo-optical switching mechanism by capturing the intricate coupling between plasmonic excitation, thermal diffusion, and semiconductor charge carrier dynamics. The numerical demonstration of all-plasmonic switching driven by LSPR-induced thermal modulation marks a possibility for advancement toward the realization of compact, high-speed all-plasmonic circuitry.

Figures used in the abstract

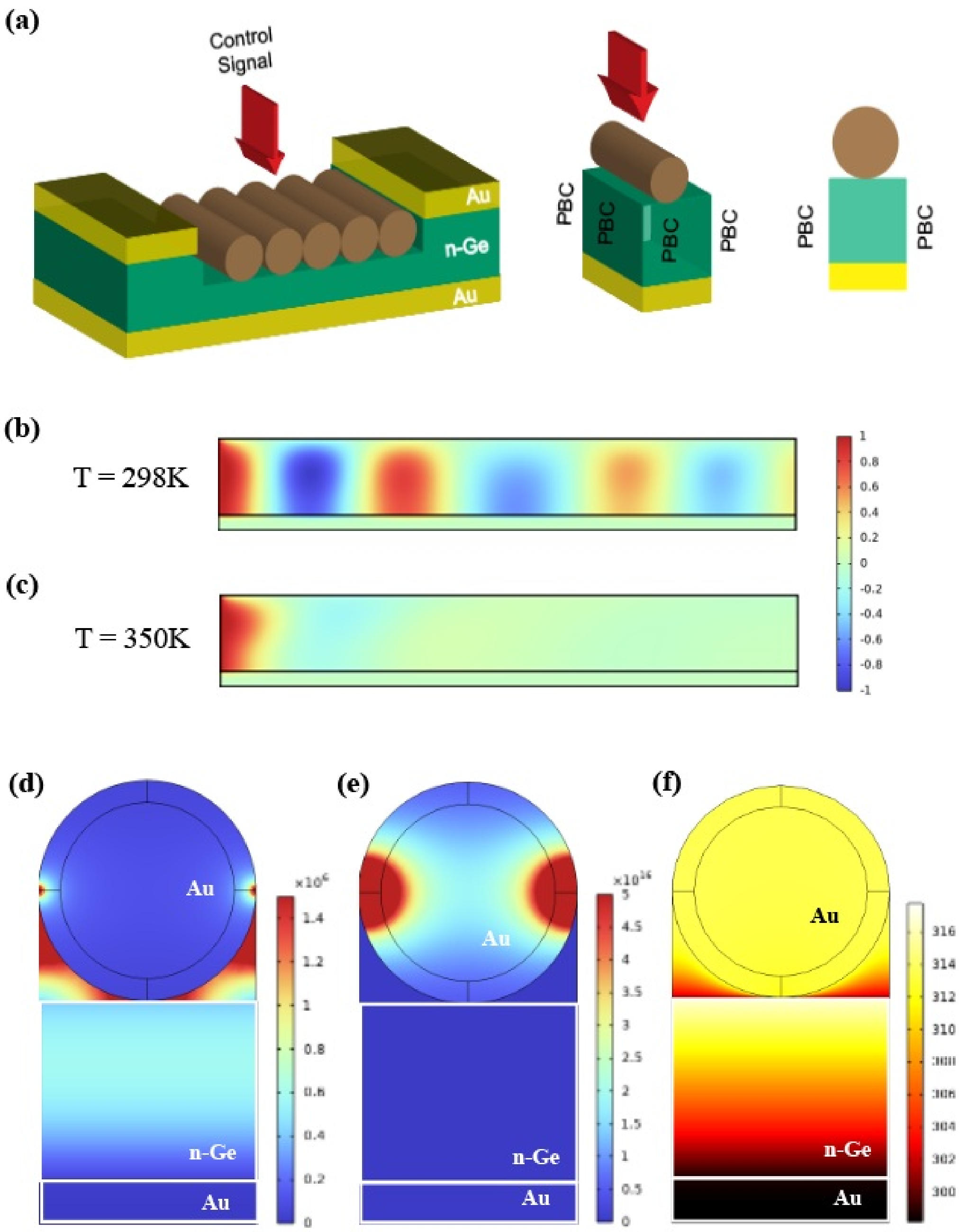

Figure 1 : (a) Schematic of the TAPS device featuring cylindrical plasmonic particles on an n-Ge/Au substrate, accompanied by both 3D and 2D visualizations of the finite-difference simulation setup. Perfectly matched layer (PML) boundary conditions are implemented o