Active Plasmonics: Controlling Signals in Au/Ga Waveguide using Nanoscale Structural Transformations

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We develop a new concept for active plasmonics exploiting nanoscale structural transformations which is supported by rigorous numerical analysis. We show that surface plasmon-polariton signals in a metal-on-dielectric waveguide containing a gallium section a few microns long can be effectively controlled by switching the structural phase of gallium. The switching may be achieved by either changing the waveguide temperature or by external optical excitation. The signal modulation depth could exceed 80 percent and switching times are expected to be in the picosecond-microsecond time scale.

We are entering the age of integrated photonic devices for signal and information processing when planar waveguides and photonic crystal structures are being intensively investigated as primary solutions for guiding light in such devices. There may however, be another means of making highly integrated optical devices, with structural elements smaller than the wavelength, enabling strong guidance and manipulation of light using metallic and metal-dielectric nanostructures. Here plasmon-polariton waves, i.e. optical excitations coupled with collective electronic excitations are used as information carriers. A range of very promising nanostructures that guide plasmon-polariton waves are currently being investigated. Surface plasmon polaritons in gold films can propagate for tens of microns and may be guided by structuring the metal film and creating polaritonic band gap materials. Propagating plasmon-polariton excitations in nanostructured metal films are therefore clearly emerging as a new information carrier for highly-integrated photonic devices. However, we will only be able to speak about 'plasmonics' in the same way that we speak about 'photronics' when efficient techniques for active manipulation of surface polariton-polariton signals are identified.

Here we propose a concept of active nanoscale functional elements operating with surface plasmon-polariton signals. Our approach takes advantage of the most characteristic features of surface plasmon-polaritons, namely their localization in nanometer thick surface layers of metal, and the fact that their propagation depends strongly on the metal's electronic properties. These features are exploited by combining them with the recently developed concept of achieving nanoscale photonic functionality using structural phase transitions in polyvalent metals, an idea which has already been shown to offer all optical switching at milliwatt power levels in thin films and nanoparticles, and promises a new type of photodetector. Here we show that surface plasmon-polariton signals in metallic on dielectric waveguides containing a gallium section a few microns long can be effectively controlled by switching the crystalline gallium section of the waveguide from one structural phase to another. The switching may be achieved by both changing the waveguide temperature and by external optical excitation. Metallic Gallium is a uniquely suitable material for this application. It is known for its polymorphism. In α-gallium, the stable 'ground-state' phase molecular and metallic properties coexist - some interatomic bonds are strong covalent bonds, forming well-defined Ga$_2$ dimers (molecules), and the rest are metallic bonds. The structure is highly anisotropic, with much better thermal and electrical conductivity in the 'metallic planes' than along the covalent bonds. Remarkably, α-gallium has a very low melting point, 29.8°C. The covalent bonding leads to a strong optical absorption peak centered at 2.3 eV and spreading from approximately 0.68 eV (∼310 nm) to the mid-infrared part of the spectrum. Optical properties of the α-Ga and more metallic phases, metastable at normal conditions, are greatly different, in terms of the dielectric coefficients of liquid gallium and solid gallium they are huge, at a wavelength of 1.55µm we have $|\varepsilon_{\text{liquid}} - \varepsilon_{\alpha}| \sim 180$. The metallic metastable phase (quasi-melt) may be achieved by simple heating, or by light absorption through a non-thermal "optical melting" mechanism via destabilization of the optically excited covalent bonding structure. Whatever the mechanism of phase transition is it is a surface mediated effect and develops as propagation of the new metallic phase from the surface into the bulk of the semiconductor-like α-phase. As the phase transition only involves a few tens of atomic layers of gallium at the interface it is highly reproducible and fully reversible and could run for millions of cycles without noticeable changes. High quality gallium interfaces with silica may be achieved using various techniques, from squeezing molten gallium to ultra-fast pulsed laser deposition.

To evaluate the potential switching characteristics of the Surface Plasmon Polariton (SPP) waveguide we numerically modelled it using the Finite Elements Method. We investigated a gold film waveguide containing gallium section of length L on a quartz substrate. To model coupling and decoupling of optical radiation to and from the waveguide two ten element meander gratings were
placed at both ends of the structure (Fig. 1). Although optimization of coupling and decoupling efficiency was not the prime objective of this study, we found that efficiencies in excess of 20% for coupling and 80% for decoupling could be achieved by the meander gratings with $s/h = 1/5$, while coupling levels above 30% are possible with gratings of complex profile. In such a waveguide the SPP wave propagates at the interface between the metal film and silica substrate, through the gold and gallium sections. SPP decay length in a continuous gold/silica waveguide is 53 µm for the excitation wavelength of 1.31 µm.

In the waveguide containing Ga section, the transmitted SPP wave attenuates due to the mismatch of dielectric characteristics at the Au-Ga border and losses which are much higher in gallium than in gold. We modelled that the gallium section of the waveguide may be converted from the ground $\alpha$-phase to the metallic liquid-like phase. We also modelled that this change could take place as interface metallization: a thin layer of metallic gallium of thickness $d$ develops at the silica interface (see Fig. 1). As $\alpha$-gallium is a highly anisotropic material (space group $Cmca$), we performed calculations of the waveguide transmission (disregarding coupling-decoupling losses) for all main crystalline orientations of the Ga film at the interface in the range of optical excitation wavelengths from 0.9 µm to 2.0 µm. Fig. 2 shows the results of these calculations at different wavelengths of incident light for a waveguide containing gallium section of length $L = 2.5 \mu m$, assuming that the gallium section is a homogeneously crystal of given orientations or is a fully molten isotropic liquid phase. The graph also show the transmission levels calculated using analytical theory which accounts for absorption in an isotropic infinite homogeneous waveguide [12] for three main values of gallium's crystalline dielectric coefficient and for the dielectric properties of the liquid state. The following notation was used: curve AB corresponds to gallium crystalline structure with its A-axis laying in the interface plane perpendicular to the direction of the SPP propagation and its B-axis perpendicular to the strip. Similar notation applies to curves BA/BC and CA/CB. The values of the complex dielectric coefficients of gallium and gold were taken from ref. [13] and [14]. Although the results of numerical analysis and analytical calculations show similar spectral trends, the magnitudes of transmission coefficients are somewhat different for these two approaches. We argue that the discrepancy reflects limitations of the analytical theory which ignores the reflection of SPPs at the gold/gallium border. More importantly, however, the analytical theory also ignores the "hopping" of the electromagnetic wave across the narrow gallium strip followed by re-coupling of the excitation into the SPP on
show that the waveguide transmission strongly depends on the structural phase of the gallium section and changing of the phase could be used for active controlling of the transmission. As the structural transformation in gallium is a surface mediated effect, two phases of gallium may co-exist at the interface, with a thin layer of metallic phase sandwiched between silica and α-Ga. In fact, melting of gallium takes the form of “surface melting” with the molten phase thickness steadily increasing with temperature in a narrow temperature corridor just below the gallium bulk melting point. Similarly, light-induced metallization also develops as a surface mediated effect and starts from the interface while the equilibrium thickness of the metallized layer \(d\) may be controlled by the light intensity. This gives a possibility of continuous, “analog” control of the waveguide transmission. To analyze this effect we calculated the waveguide transmission for different thicknesses of metastable gallium phase up to \(d = 60 \text{nm}\) for a number of incident wavelengths (see Fig.3). For illustrative purposes the gallium strip was taken to be polycrystalline α-Ga: isotropic with dielectric constants averaged over crystal directions. In can be seen that the presence of the metallic liquid Ga layer in the section of only a few microns long and depth of just \(d = 30 \text{ nm}\) can dramatically change the transmission of plasmons through the waveguide.

One therefore can envisage an active plasmonic devise in which SPP transmission is controlled by the waveguide temperature in the range of a few degrees or external optical stimulation. In the near-infrared part of the spectrum a typical fluence of optical excitation needed for converting of α-Ga phase to a metallic phase of several tens of nanometers deep is about 10 mJ/cm\(^2\). For a section of gallium waveguide 2.5 μm x 2.5 μm the optical energy required for high-contrast switching would be in the order of 10 pJ. The envisaged application of the control light signal to the waveguide is schematically presented on Fig.1 by a dashed arrow. When the excitation is terminated the molten/metallic layer rapidly recrystallizes into the ground α-phase. The intrinsic switch-on time was measured for a gallium-quartz interface, and was found to be 2-4 ps and we expect that the SPP switch-on time will also be in the scale of a few ps. We anticipate the SPP switch-off time to be in the microsecond-nanosecond time scales. Notably, this is 4-8 orders of magnitude faster than the currently achieved response time of opto-mechanical switching microdevices.

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\[\text{FIG. 3: Waveguide transmission as a function of the depth} \ d \ \text{of the metallic gallium layer. Insert shows the dependence of transmission on the width} \ L \ \text{of gallium section.}\]