APPLIED PHYSICS LETTERS **88**, 082106 (2006)

Low-frequency active surface plasmon optics on semiconductors

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(Received 20 May 2005; accepted 5 January 2006; published online 23 February 2006)

A major challenge in the development of surface plasmon optics or plasmonics is the active control of the propagation of surface plasmon polaritons (SPPs). Here, we demonstrate the feasibility of low-frequency active plasmonics using semiconductors. We show experimentally that the Bragg scattering of terahertz SPPs on a semiconductor grating can be modified by thermal excitation of free carriers. The transmission of SPPs through the grating at certain frequencies can be switched completely by changing the temperature less than 100 °C. This semiconductor switch provides a basis for the development of low-frequency surface-plasmon optical devices. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2177348]

Electromagnetic waves are usually controlled on length scales larger than their wave length. However, this limit can be overcome with low-dimensional waves, such as surface plasmon polaritons (SPPs). SPPs are electromagnetic waves bounded to the interface between a conductor and a dielectric, and coupled to the oscillation of free charge carriers. The strong field confinement to the surface is the reason why SPPs are used as "light" for subwavelength optics and as probe for sensitive spectroscopy of species close to the conductor. The recent observation of a wealth of surface-plasmon-mediated phenomena has sparked a huge scientific and technological interest in surface plasmon optics or plasmonics.[1] In this regard, a mayor challenge of surface plasmon optics is the active control of the SPP propagation. Active plasmonics in the optical range has been recently demonstrated,[2–4] opening this field to exciting possibilities.

Here, we demonstrate the feasibility of highly efficient and broadband active surface plasmon optics at low frequencies using semiconductors instead of metals for the propagation of SPPs. We show that the propagation of far-infrared or terahertz SPPs on a semiconductor grating or Bragg mirror can be switched completely by thermal excitation of free carriers. The propagation of SPPs and their characteristic decay lengths away from the surface depend on the permittivities of the dielectric and the conductor. The dielectric is usually air with a permittivity equal to one, and the conductor has a negative permittivity ϵ determined by the plasma frequency ν_p, which is proportional to the square root of free-charge-carrier density. The plasma frequency of metals is usually in the ultraviolet or in the visible part of the electromagnetic spectrum, leading to small absolute values of the permittivity at optical frequencies, and thus in turn to a short SPP decay length into air (~ 100 nm), which results in an enhanced electromagnetic energy density at the interface.[5] However, $|\epsilon| \gtrsim 10^5$ at terahertz and microwave frequencies, which leads to huge SPP decay lengths on the order of several centimetres. This weak-field confinement limits the usefulness of low-frequency plasmonics for applications where a large enhancement and localization of the electromagnetic field is required.

The metallic character of doped semiconductors at low frequencies makes it possible to excite SPPs at midinfrared, THz, and microwave frequencies.[6,7] As the carrier densities in semiconductors are much lower than those in metals, the plasma frequency is much smaller, being typically at mid- or far-infrared frequencies. Therefore, the permittivity of semiconductors at terahertz and microwave frequencies is comparable to that of metals at optical frequencies. A decisive advantage of semiconductors is that their carrier density and mobility, and consequently the SPPs, can be easily controlled by thermal excitation of free carriers.

We report on the control of the SPPs propagation across a grating of 30 grooves with a lattice constant of 442 μm structured in intrinsic (undoped) indium antimonide. The grating was prepared by dicing grooves with a programmable dicing saw on a 2 in. wafer 480 μm thick. The grooves are thus parallel cuts with a depth of 70 μm and a width of 213 μm. InSb is a semiconductor with a small energy gap of 0.17 eV and a very large electronic mobility. The effective electron mass is $0.014 m_o$. The density of thermally excited carriers at room temperature is $N \simeq 10^{16}$ cm^{-3} and the electronic mobility $\mu \simeq 7.7 \times 10^4$ cm^2 V^{-1} s^{-1} (cf. Ref. 8). At this temperature the corresponding plasma frequency lies around 2 THz. The hole mobility is two orders of magnitude smaller than the electron mobility, thus making the metallic character of InSb with the same hole and electron density (undoped) be mainly determined by the electrons.[8] As the temperature is lowered, the density of thermally excited carriers is reduced and their mobility increases. At −35 °C, $N \simeq 0.3 \times 10^{16}$ cm^{-3} and $\mu \simeq 11 \times 10^4$ cm^2 V^{-1} s^{-1}, and the plasma frequency is reduced to $\simeq 1$ THz (cf. Ref. 9).

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We use a THz-time domain spectrometer capable of measuring the amplitude of the THz field as function of time. In this setup, a train of ultrashort optical pulses from a Ti:Sapphire laser is split into two beams. One of these beams is used to optically generate coherent and linearly polarized THz radiation from an InGaAs surface field emitter. The other beam gates a photoconductive antenna which detects the THz field. By varying the time delay between the two pulse trains, the THz pulse amplitude can be detected as a function of time with subpicosecond resolution. To excite broadband SPPs on the surface of the semiconductor, we use the aperture coupling technique,[10,11] preferred over other, more efficient methods, which are however narrow band. THz radiation with the electric field parallel to the plane of incidence (p polarization) is scattered at the aperture defined by the edge of a razor blade and the surface of the sample. The scattered waves comprise a continuum of both propagating and evanescent waves, and makes it possible the excitation of SPPs, which propagate along the surface mostly at a range of directions about the perpendicular to the razor blade and the groove axis. A second blade placed at a distance of 2 cm from the first one is used to couple back the SPPs into free propagating radiation which is detected. We should stress at this point that the grating used in the experiments is not intended to act as a coupling device. We study the propagation of SPPs across the grating and its Bragg scattering aiming to control the SPP transmission.

The wafer where the grating is structured was placed on top of a thermoelectric cooler capable to heat up to 55 °C and to cool down to −40 °C. The temperature was measured with a PT100 resistor glued onto the wafer and stabilized by a feedback loop with the power supply of the cooler.

The dispersion relation of SPPs at room temperature on a grating of InSb with the same groove depth, width and lattice constant as those used in the experiments is represented by the solid curve of Fig. 1(a), calculated from the homogeneous reduced Rayleigh equation obtained upon imposing an impedance boundary condition.[12] The dotted line in Fig. 1(a) corresponds to the light line. The SPPs dispersion relation deviates from the light line opening a gap around 0.3 THz. This gap is a consequence of the Bragg scattering of SPPs.[13–16] The upper band intercepts the light line at $\nu = 0.335$ THz. At higher frequencies, SPPs become leaky waves, thus being coupled by the grating to freely propagating electromagnetic radiation.

The terahertz pulses were measured in the time interval of 0–130 ps, with the maximum pulse amplitude around 10 ps. The pulses were made symmetric by extending the time-domain signals with zeros to negative times up to −110 ps (zero padding). The transmission is defined as the power spectrum of the transmitted pulses calculated by Fourier transforming the signals; the characteristics of the pulse measurements (time resolution and span) guarantee that a large spectral range is covered with the required resolution, as will be evident below. The transmittance is obtained by normalizing the transmission through the grating by the spectrum of SPPs propagating the same distance on a flat InSb surface. Figure 1(b) depicts the transmittance of SPPs through the grating at room temperature. A strong reduction of the transmittance around 0.3 THz, i.e., at the gap frequencies, is observed. At frequencies within the gap, the SPPs reflected at individual grooves interfere constructively, giving rise to a negligible transmittance of 0.1%. The transmittance does not reach unity at high frequencies due to radiative leakage consequence of the crossing of the SPP dispersion relation with the light line.[17]

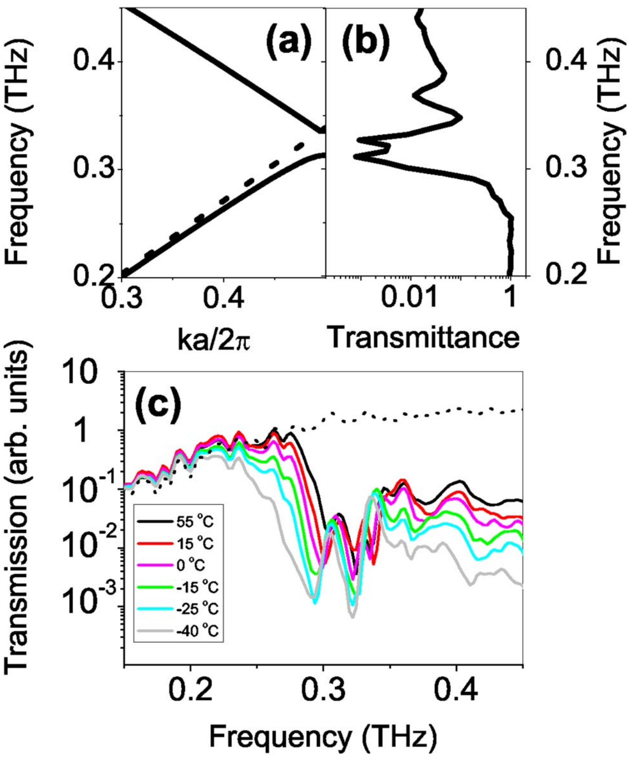

FIG. 1. (Color online) (a) The solid line represents the dispersion relation of SPPs propagating on an InSb grating with a lattice constant of 442 μm formed by grooves with a width of 221 μm and a depth of 70 μm. The dashed line is the light line (b) Transmittance of SPPs through the grating at room temperature, defined as the transmitted power spectrum normalized by the spectrum of SPPs propagating on a flat InSb surface. (c) SPP power spectra. The dotted line corresponds to the reference spectrum measured on a flat InSb wafer at room temperature. The other lines are the SPP transmission at different temperatures.

The SPP transmission through the grating at different temperatures is presented in Fig. 1(c). The dotted line is the spectrum of SPPs after propagating on a flat InSb surface at room temperature. As the temperature is reduced, the number of free charge carriers drops and the plasma frequency ν_p shifts to lower values, leading to a better confinement of the SPPs to the surface and to a stronger scattering.[12,18] Consequently, the gap becomes wider and deeper, and leakage at high frequencies increases. As a result of the widening of the gap, the low-frequency band edge shifts by more than 40 GHz, which corresponds to 65% of the gap width at room temperature. This shift represents a ultrabroadband active switch for SPPs.

To better illustrate the thermal switching of the transmission, we plot in Fig. 2(a) the spectra of the SPPs transmitted through the grating at different temperatures normalized by that measured at the highest temperature, i.e., 55 °C. This ratio is proportional to the inverse of the switching efficiency. Due to the widening of the gap, the ratio decreases strongly around 0.29 THz as the temperature of the grating is reduced; it increases slightly at 0.31 and 0.34 THz, and decreases at higher frequencies or in the region of losses. To validate this experimental observation, we have calculated the SPP transmission through a grating of grooves with the same geometry as in the experiments and a temperature dependent permittivity. For the calculations, we employ the rig-

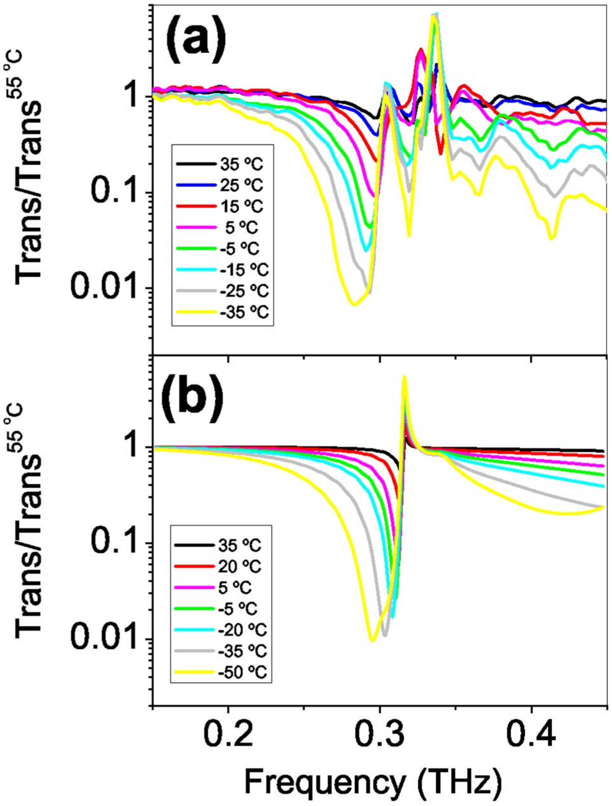

FIG. 2. (Color online) Transmission power spectra of surface plasmon polaritons through an InSb grating at different temperatures normalized by the transmission at 55 °C. (a) Measurements. (b) Numerical calculations.

orous electromagnetic formulation of the Green's theorem, surface integral equations.[19] To reproduce the experimental configuration, a one-dimensional surface is considered separating vacuum from a semi-infinite semiconductor. Instead of a razor blade and an incident THz pulse, a finite sinusoidal grating illuminated by a monochromatic, focused Gaussian beam is used with grating period tuned to excite SPPs.[20] The frequency dependence of the intensity of the SPP transmitted through the groove array is obtained from the electromagnetic field intensity at the position given by the outcoupling razor blade, normalized by that obtained in the absence of the groove array (flat surface). The results of these calculations are presented in Fig. 2(b). Keeping in mind that we do not use any fitting parameter, there is a very good agreement between theory and experiment. Slight quantitative discrepancies appear, however, which are enlarged by the normalization procedure.

The minimum of the transmission ratio of Fig. 2 at the low-frequency band edge is displayed in Fig. 3 as a function of temperature. The circles are experimental results, while the triangles represent calculations. The switching efficiency reaches the extraordinarily high value of 99.3%, i.e., the SPPs transmission through the grating is virtually suppressed at 0.29 THz by varying the temperature less than 100 °C. This change in temperature corresponds to a modification in the carrier density[9] Between $\simeq 0.2$ and 1.8×10^{16} cm^{-3}, as displayed in the upper abscissa axis of Fig. 3.

In conclusion, we have demonstrated that semiconductors are good candidates for the emerging field of active surface plasmon optics. In particular, we have shown that the Bragg scattering of terahertz surface plasmon polaritons on a

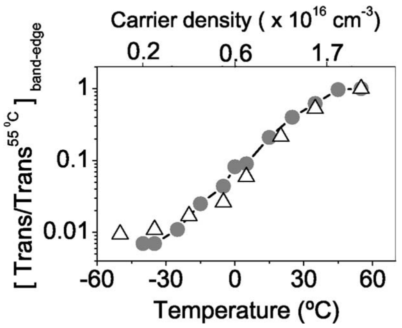

FIG. 3. Transmission of surface plasmon polaritons through an InSb grating at the low-frequency band edge normalized by the transmission at 55 °C vs the temperature of the grating. The circles are the measurements, while the triangles represent numerical calculations. The upper abscissa axis indicates the thermally excited carrier density.

grating structured in InSb can be modified by thermal excitation of free carriers. A switching efficiency of nearly two orders of magnitude is rendered possible by changing the temperature less than 100 °C. Moreover, we anticipate that the possibility of exciting carriers optically rather than thermally will permit ultrafast plasmonics at very low fluences.

The authors gratefully acknowledges financial support from the European Union through the projects Interactton (HPRN-CT-2002-00206) and Metamorphose (NMP3-CT-2004-500252), and from the Deutsche Forschungsgemeinschaft. The work of one of the authors (J.A.S.G.) was supported in part by the Spanish Comunidad de Madrid (Grant No. GR/MAT/0425/2004) and MEC (Grant Nos. BFM2003-0427 and FIS2004-0108).

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