Opto-electronic versus electro-optic modulation

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We present a nonlinear modulation scheme based on coupling between optically excited surface plasmons in a thin gold film and the heating of the film by a pulsed direct current, and also for the reverse process. The reflected surface-plasmon excitation beam is shown to undergo a spatial deformation as a function of a pulsed current through the foil. Similarly, the current through the thin film is modulated by the action of periodic excitation of surface plasmons using infrared photons. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1804252]

The transfer of information by modulating a carrier of a given form of energy may involve modulation via either the same form of energy or a quite different form. In the latter case, it is sometimes advantageous to induce modulation by an effect that has a reciprocal. In this event, the form of energy used for modulation can be replaced with the form used for the carrier and that of the carrier can be replaced with that of the modulator. While the efficiency of the communication system might be different after such an exchange, the results may be adequate, but the greatest advantage typically occurs when the efficiency is not severely altered. For example, electronic modulation of an electromagnetic wave is the reciprocal of the modulation of electronic signals by the wave as it is converted by a receiving antenna. In this letter we discuss a modulation method in which four different forms of energy are involved. In particular, we present the results of experiments that utilize photons, surface plasmons, phonons, and electrical current. We show that excitation of surface plasmons in thin gold wires by a pulsed beam of photons produces modulation of electrical current in the wires and that modulation of the current can in turn produce a modulated beam of photons. The thermal effects of surface plasmons are central to the process. However, the energies are well below those required for an induced phase change such as may be encountered in the well-known photothermal phenomena. As a result, the surface-plasmon–phonon process can provide much more rapid information transfer. Recently, we reported[1] a nonlinear coupling scheme that involves several spectrally different surface plasmons in an analogous configuration to the one presented here. However, the basis of the former scheme was all optical modulation of surface plasmons excited at visible and infrared photon energies with no involvement of electrical modulation.

Surface plasmons were discussed by Ritchie in 1957 in connection with energy losses by fast electrons impinging upon a metal surface.[2,3] Soon after this, there were a number of methods discovered in which surface plasmons are excited by photons, the most widely used being the Kretschmann configuration.[4] This configuration has provided many analytical applications as well as basic studies of a range of surface phenomena. In the experiments described below, we use the Kretschmann configuration for modulation studies. This arrangement is shown to provide a simple method of modulating electrical current by photons ($p \rightarrow c$) or inversely to provide modulation of a beam of photons by electrical current ($c \rightarrow p$). The results are somewhat surprising in that the broad exploitation of surface plasmons has not previously produced evidence of this interesting set of results. The effects could be applied to studies of the contribution of surface plasmons to the resistance of thin wires. For example, if a constant potential difference is maintained across a wire, then its resistance can vary with surface-plasmon excitation as a result of the plasmon-current coupling.

Our experimental arrangement is displayed schematically in Fig. 1. Using a mask, two thick chromium film pads are vacuum evaporated onto a quartz substrate, after which, using a second mask, a thin gold film is evaporated to form narrow lines. The pads are connected to external electronics to facilitate a steady or pulsed current flow. Thus, electron flow in the $p \rightarrow c$ ($c \rightarrow p$) process is induced by maintaining a constant (oscillating) potential difference at two mirror points on the foil boundary. In order to observe the $c \rightarrow p$ process, Fig. 1(a), the $\lambda = 442$-nm line of a helium-cadmium (HeCd) laser (Kimmon) is used, while the current is modulated electronically using a direct current power supply (Agilent, software controlled for modulation). The p-polarized beam (10 mW) is incident at 60° to stimulate the surface plasmons while a laser beam profiler (BeamStar-2000, Ophir Optronics) is used to diagnose and record the reflected beam. During the $p \rightarrow c$ process, Fig. 1(b), the $\lambda = 1550$-nm (<500 mW) line of a continuous wave laser (Streamline-RL, Spectra-Physics), incident at 46°, is used in combination with a polarization rotator to stimulate the surface plasmons in the spectrally optimized gold film (29.5 nm thick for $\lambda = 1550$ nm). A sensitive infrared detector module (InGaAs, noncooled-type, matched preamplifier, Hamamatsu), and an infrared viewer (MicronViewer, Electrophysics) are used for beam steering, delivery, and surface-plasmon resonance op-

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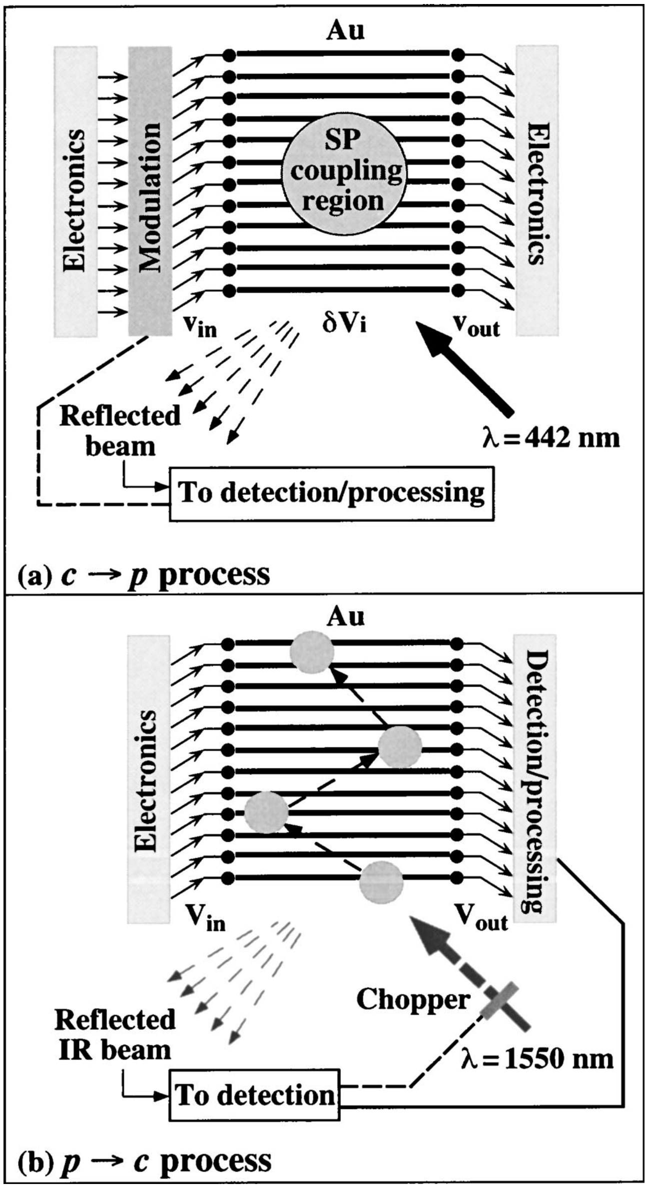

FIG. 1. Schematic diagram of the experimental arrangements. The structures (with their top view shown) reside on a quartz prism substrate as in the Kretschmann configuration with the beams (shaded circles) entering from the substrate side. (a) depicts the $(c \to p)$ process for modulation of the reflected surface-plasmon excitation beam by an array of current carrying gold lines of variable potential difference δV_i. The reflected field of a spatially filtered (variable diameter) surface-plasmon excitation beam may be controlled by the action of the selected current carrying gold lines. The reverse process $(p \to c)$ is illustrated in (b), where an amplitude modulated p-polarized infrared beam excites the surface plasmons, which in turn induce modulation in the current carrying gold lines. The beam may be scanned in any chosen manner. A common feature of both processes $p \leftrightarrows c$ is the feasibility of multiple wavelength excitation and/or modulation.

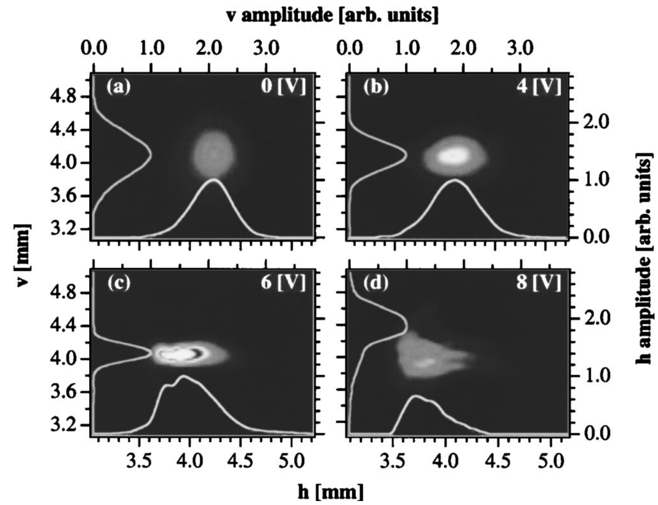

FIG. 2. Modulation of the surface-plasmon excitation by the action of the electron flow through the excitation region, i.e., the $c \to p$ process. The profiles shown were recorded in vh plane perpendicular to the direction of the propagation of the reflected beams. The line profiles are taken through the point of maximum intensity. (a) displays the profile of the reflected excitation beam prior to the current flow. A 4-V potential difference across the gold film (which induces the resistivity of the film to be non-Ohmic) causes the beam profile to undergo a lateral spatial deformation similar to focusing of the beam, shown in (b), which becomes more pronounced for higher voltages (or currents) as shown in (c). For higher voltages, the beam scatters and no well-defined boundary can be observed as shown in (d). For even higher potentials, the beam completely vanishes.

timization. Lock-in detection is used to measure the modulation amplitude in both cases.

The results are shown in Fig. 2 for the $c \to p$ process. The resonance conditions of the surface plasmons are altered due to the action of the electron flow modifying the dielectric function of the metal, resulting in a spatial variation of the beam in the form of an initial focusing for lower potential differences, Figs. 2(b) and 2(c), and a subsequent expansion for higher differences, Fig. 2(d). The temperature-dependent part of the resistance of a metal film may have several contributions, such as electron-electron and electron-phonon interactions. Thus, the optical properties of the substrate-film system are changed as a result of the current flow (Fig. 2). Such thermo-optic modifications may be explained in terms of the temperature dependence of the dielectric function of the entire system. A theoretical approach which describes the coupling is being developed, based on the simultaneous solutions of a system of partial differential equations describing the propagation of the optical fields, and the conduction of heat and current in the thin gold film. The inelastic scattering of the electrons in the current in the $c \to p$ process increases the temperature of the gold film, which in turn alters the conductivity of the film. This is further depicted in Fig. 3(a), which shows the resistance of the gold foil in the Ohmic and non-Ohmic regions. For a nominal film resistance of 3.46 Ω, the non-Ohmic region appears clearly for current values above 0.6 A. The beam characteristics appear to be altered for potential differences approximately at 4 V [see Fig. 2(b)], which as can be confirmed from Fig. 3(a), is where the non-Ohmic behavior commences, i.e., a resistance change occurs. The beam distortion is highest [Fig. 2(d)] in the higher non-Ohmic region (where departure from 3.46 Ω is largest). This is currently being investigated in our model in terms of the temperature dependence of a Drude dielectric function of the gold film. A number of studies, related to electrical and thermal conductivities, have been reported for thin gold films on dielectric substrates or embedded in multilayer structures.[5–11]

Alternatively, in the $p \to c$ process, the loss of surface-plasmon energy to phonons results in a temperature rise in the foil, which modifies the conductivity of the foil and thus induces a measurable change in the current through the foil. To measure this change, a relatively simple electronic circuit which incorporates the foil as a passive element is used. By pulsing the incident infrared surface plasmon excitation beam by the use of a mechanical chopper, and monitoring the

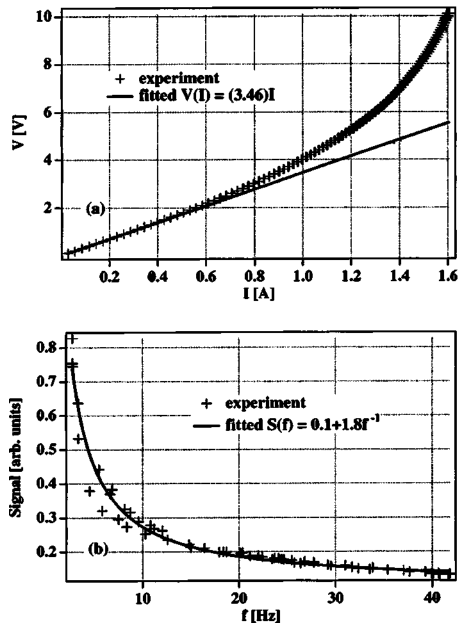

FIG. 3. (a) The Ohmic and non-Ohmic regions for the resistance of the gold foil with a thickness of 29.5 nm. As can be seen from the potential–current (V–I) measurement, the non-Ohmic region $[V(I) > 3.46I]$ of the film resistance $R\ \Omega$ enters at around 0.6 A, and for the current range studied the overall behavior has a higher-order dependence. (b) The frequency dependence of the $(p \rightarrow c)$ modulation of the current by the surface-plasmon excitation at $\lambda = 1550$ nm. An inverse frequency dependence as shown by the fitted function $S(f)$ appears to represent the data well.

current through the film by a lock-in amplifier, a pulsing current can be measured. The signal obtained is shown in Fig. 3(b) as a function of the laser beam modulation frequency f. An inverse frequency dependence is seen to describe the data in Fig. 3(b) well. However, this representation may not be unique, and the actual functional frequency dependence of the observed effect is under investigation. The detection limit can be improved by the choice of an appropriate foil material, and with improved electronics.

In conclusion, we have investigated the interaction between coherent electronic fluctuations and noncoherent electron flow in a thin foil by presenting the results of coupling between optically excited surface plasmons and a current in a thin gold film. The interaction, presented as a nonlinear coupling, opens the possibilities of opto-electronic and electro-optic modulation schemes. We have shown that this coupling can be sustained in a broad spectral range appropriate for the operation of many photonic applications. Based on the results presented here, it is conceivable that by varying the frequency, amplitude, and waveform of the current through the film, or the polarization, incidence angle, intensity, and wavelength of the surface-plasmon excitation beam, a communication or information transfer scheme can be established.

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