Electron tunneling stimulated by surface plasmons

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An increase in the conductivity of laser-irradiated tunneling junctions has been observed in experiment. The increment to the tunnel current depends on the type of metal, on the polarity of the applied voltage, and on the wavelength and polarization of the optical radiation. The results are interpreted as a consequence of inelastic interaction of the tunneling electrons with the plasmons of the metallic electrode.

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Lambe and McCarthy[1] have recently reported emission of light, in a wide spectral range, following inealstic tunneling of electrons in metal—insulator—metal (MIM) film structures. At a given bias V on the junction, the maximum emission

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frequency corresponded to the quantum relation $h\nu_{\max}=eV$. One can expect exposure of the junction to light to produce an inverse effect, consisting of a variation of the tunneling current at voltages $eV \geqslant h\nu$, and having a mechanism analogous to the direct Lambe-McCarthy effect. The observation and investigation of this inverse effect is of interest for the understanding of the mechanism of the described phenomena.

The purpose of the present study was to observe a photoinduced tunneling current due to inelastic interaction of electrons and photons with surface plasmons, a process invoked by Lambe and McCarthy to explain their results. The difficulty of separating this effect lies in the presence of other mechanisms that alter the tunneling current under the influence of light and are not connected with plasmons.[2,3] We have therefore investigated the dependence of the increment to the current on the type of metal, on the polarity of the applied voltage, on the wavelength and on the polarization of the radiation.

Tunneling junctions with a base electrode of aluminum or magnesium were produced on sapphire substrate by condensation in vacuum. The thickness of the base fil was ~1000 Å. The upper film of Ag, Al, Cu, Mg or Sn, through which the junctio was irradiated, was made semitransparent with thickness 100–300 Å, and its transmission was measured with a microphotometer. The oxide-layer thickness was 30–40 Å The resistance of the tunneling junctions at zero bias ranged from several units t several dozen megohms. All the measurements were made at 77 K. The samples wer placed directly in liquid nitrogen, or in an atmosphere of helium gas. The radiatio from the He-Ne laser ($\lambda_1=0.63$ μm and $\lambda_2=1.15$ μm) was fed into the cryostat via light pipe or through the side walls. The useful signal δV was registered by a synchronous-detection circuit with the laser-beam intensity modulated at 420 Hz. In the experiments we recorded the current-voltage characteristic $V(I)$ without irradiation an the alternating voltage $\delta V(I)$ produced across the sample under the influence of th

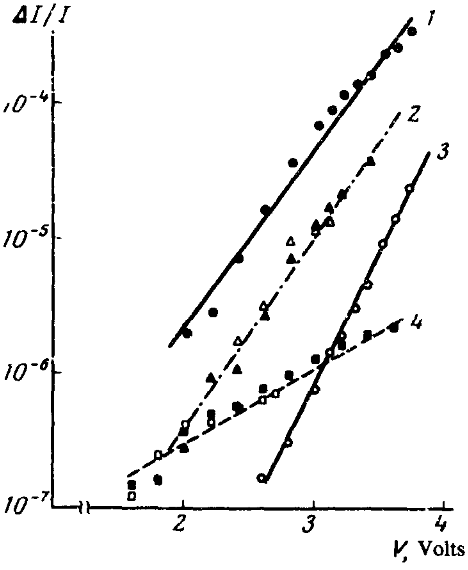

FIG. 1. Relative increase of the tunnel curre under the influence of the irradiation as a fun tion of the bias on the junctions Al–A (1—$\lambda_1=0.63$ μm, 3—$\lambda_2=1.15$ μm), Al– (2—$\lambda_1=0.63$ μm), Al–Cu (4—$\lambda_1=0.6$ μm—■, $\lambda_2=1.15$ μm—□). The radiation po er density 70 mW/cm².

external radiation. From these relations we calculated the derivative $dI/dV(V)$ and the increment to the tunnel current $\Delta I(V)$.[4] The measurements were performed only on junctions with clearly pronounced asymmetry of the current-voltage characteristics at large biases, thus attesting to the tunneling character of the flowing current.

Figure 1 shows plots of the relative increment $\Delta I/I$ of tunnel current against the voltage. $\Delta I/I$ had a linear dependence on the incident-radiation power and the sign of ΔV changed with changing direction of the current through the junction. The curves on Fig. 1 were normalized to equal intensity of irradiation of the aluminum-film base. The polarity of the voltage was such that the electrons tunneled from the lower aluminum film to the upper silver or copper film. When the polarity was reversed, the values of $\Delta I/I$ for these junctions were smaller by a factor 30–50, so that we were able to neglect the influence of ordinary heating by the radiation. The characteristics of the Al-Sn junctions were similar and are not shown in Fig. 1. Usually $\Delta I/I$ is larger for the shorter-wavelength light.

For the Al–Al oxide–Al junction the value of $\Delta I/I$ does not depend on the polarity (dark and light triangles on line 2). On the other hand, from the similarity of the current-voltage characteristics of the Al–Al and Al–Ag junctions it follows that the potential barriers in these junctions have approximately the same shape. Consequently, the observed differences between the functions $\Delta I/I(V)$ are due to processes occurring in the upper metallic film (Ag).

To observe the interaction of the light with the surface plasmons, we measured δV as a function of the angle of incidence θ of the irradiation on the junction for p and s polarizations at a constant bias $V=3.9$ V. It turned out that δV_p and δV_s, which are equal at $V=0$, do not increase at the same rate with increasing θ. The difference between these quantities, referred to $\delta V(\theta=0)$, is shown in Fig. 2. An analogous

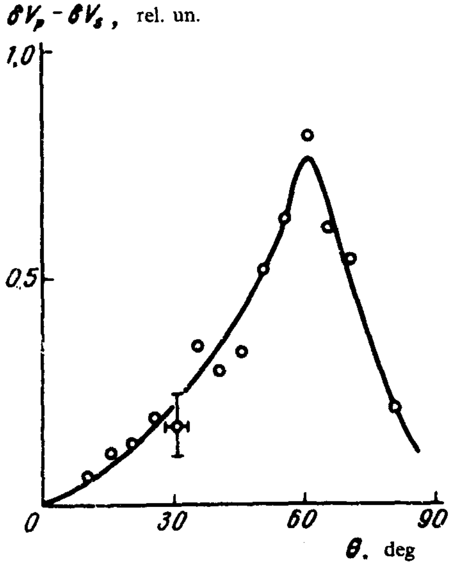

FIG. 2. Angular dependence of the differences, referred to $\theta=0°$, of the junction voltages induced by light of $\lambda=0.63$ μm, for p and s polarizations of the incident radiation. Al–Ag junction.

dependence for $V=0$ was obtained in[5], where the photon energy coincided with the energy of the plasma oscillations in silver. In our case, the photon energy (1.97 eV) is lower than the silver volume plasmon (3.8 eV) and seems to correspond to excitation of low-lying surface plasmons.

The electrons tunneling from aluminum to Ag(Cu,Sn) thus excite low-lying plasmons, and this leads to a tunnel-current increment caused by these inelastic processes. The transparency of such an inelastic tunneling channel depends on the external radiation on account of the interaction of the light with the plasmons, as follows from Fig. 2. From this point of view, it becomes clear why the effect in copper is independent of the wavelength of the light (curve 4 on Fig. 1), and also why there is no effect in Al–Al oxide–Mg, Mg–Mg oxide–Al, and Al–Al junctions. In the first case it must be recognized that the frequency of the surface plasmons in copper lies below 2 eV. In the second case it must be taken into account that the frequencies of the surface plasmons for aluminum and magnesium lie far from the frequency of the incident radiation (5–10 eV). It should be noted, however, that no photoinduced currents were observed by us in Mg–Mg oxide–Al junctions, a fact probably due in part to the smallness of the relaxation time of the "hot" electrons in magnesium in comparison with aluminum. All the experimental results noted above were well reproduced in different junctions of one and the same type.

We note in conclusion that despite the indicated exceptions, which are of interest by themselves, the results definitely attest to participation of plasmons in the mechanism whereby photoinduced tunnel currents are produced.

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