Prism-Coupled Light Emission from Tunnel Junctions

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We have observed completely *p*-polarized light emission from smooth Al-AlO$_x$-Au tunnel junctions placed on a prism coupler. The angle and polarization dependence demonstrate unambiguously that the emitted light is radiated by the fast-mode surface plasmon polariton. The emission spectra suggest that the dominant process for the excitation of the fast mode is through conversion of the slow mode to the fast mode mediated by residual roughness on the junction surface.

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Since the initial discovery of light emission from metal-oxide-metal tunnel junctions by Lambe and McCarthy,[1] many groups have studied the properties of these light-emitting tunnel junctions both experimentally and theoretically.[2-12] In all the previous studies the presence of surface roughness or corrugation[6] on the junction area was essential in providing an efficient emission mechanism. The role of surface roughness is to modify the wave-vector conservation along the surface and to permit wave-vector matching between the external free photons and the surface plasmon polaritons (SPP) created and confined in the junction geometry. For the first time we have fabricated and studied light-emitting tunnel junctions whose primary light-emission mechanism does not depend on surface roughness. We accomplish wave-vector matching and resultant light emission by fabricating a *nominally smooth* junction on a coupler prism as sketched in the inset of Fig. 1. A great advantage of this new method is that the primary emission mechanism does not involve surface roughness which is difficult to quantify experimentally, requires additional assumptions in theory, and on the whole introduces ambiguities to both theory and experiment. Because the light-emission part of the process is simple and straightforward, we can concentrate on unraveling the excitation mechanisms of different SPP modes in the junction as we describe below.

Consider the sample geometry shown in the inset of Fig. 1 where an Al-AlO$_x$-Au tunnel junction is placed on the flat bottom surface of a hemicylindrical glass prism. The normal electromagnetic modes (SPP) of this five-layered structure have three dispersion branches shown in Fig. 1. The lowest-frequency branch is the so-called "slow mode" whose electric field is concentrated in the oxide layer. The middle mode has its field concentrated at the Al-prism interface, and the highest-frequency mode is the so-called "fast mode" which is mostly localized at the Au-vacuum interface. Notice that the infrared and visible portion of this branch lies to the left of the light line for the prism; hence, this mode is radiative in the prism. Since the dispersion curve of this mode lies very close to the vacuum light line, the component of its wave vector parallel to the interface is given by

$$k_{\parallel}(\text{fast mode}) \cong \omega/c,$$

where ω is the frequency and c is the speed of light in vacuum. On the other hand, the parallel component of the wave vector of light in the prism is given by

$$k_{\parallel}(\text{light}) = (n_p\omega/c)\sin\theta,$$

where n_p is the refractive index of the prism and θ is the angle between the surface normal and the direction of the propagation of light in the prism. Therefore, the parallel-wave-vector matching condition is

$$\sin\theta \cong 1/n_p.$$

The angle θ given by this equation is the critical angle for total internal reflection in the prism, which for BK-7 glass ($n_p = 1.518$) is approximately 41°. Since the dispersion curve is essentially straight and close to the vacuum light line in the visible region, we expect light of all frequencies from the fast mode to be emitted at a single angle along the surface of a cone. This

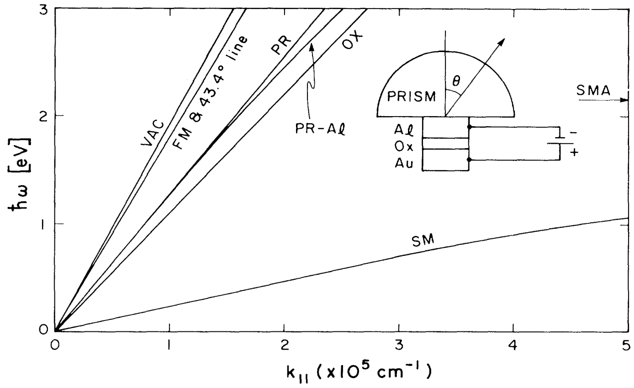

FIG. 1. Dispersion curves of the three SPP modes in the tunnel junction. SM, slow mode; FM, fast mode; PR-Al, prism-Al interface mode; VAC, vacuum light line; PR, prism light line; OX, oxide light line; SMA, asymptotic frequency of SM at large $k_{\parallel}$. The inset shows the geometry of the tunnel junction on the flat surface of a hemicylindrical prism.

emission should be polarized in the sagittal plane (p polarized). From the exact calculation of the dispersion curve, we find that $\theta = 43.4°$ at 2.12 eV (5850 Å) and the exact angle of emission varies slightly with energy because of the slight curvature of the dispersion curve.

Figure 2(a) shows a photograph of the light-emission pattern from a tunnel junction sketched in the inset of Fig. 1. The nominal thicknesses of the Al and Au films were 175 and 325 Å, respectively.[13] This photograph was taken by simply placing a film above the hemicylindrical prism without any optics between the film and the prism. The shape of the pattern seen here is the result of refraction of a cone of light through a hemicylindrical prism, and from the distances involved we determined the apex angle of the emission cone to be ~44°, in agreement with the above considerations. In a color photograph the small-angle side of the emission pattern is red and the large-angle side is blue. Figure 2(b) shows a plot of the emission-angle dependence of the intensity at 5850 Å. We obtained this plot by setting a spectrometer for transmission at 5850 Å and rotating the prism at the focal point of the input optics. We see that the maximum amount of p-polarized light is emitted at 44° ±0.5° with the full width at half maximum of approximately 3°, which is mainly due to the finite size of the junction. The intensity of the s-polarized light in this angle range is constant at less than 10% of the peak intensity of the p-polarized light. The angle dependence and the polarization of the emitted light show unequivocally that it is the fast mode that radiates.

Figure 3 shows the spectra of the emitted light at three separate angles. These spectra are corrected for the detection efficiency and the throughput of the spectrometer-photomultiplier system. We note that the spectra cut off near the upper limit given by $\hbar\omega = eV_0$ as expected (V_0 is the applied bias voltage), but do not spread down to the infrared as envisioned by the simple kinematic picture. Instead, the emission is concentrated in the range between 5500 and 6500 Å, and when V_0 is above ~2.5 V the peak position is independent of the bias voltage.

To understand the spectra seen in Fig. 3, we have formulated a theory of light emission through a coupler prism[13] by adapting the theory of Laks and Mills[10] to our geometry. If we assume a simple form for the current fluctuation in the junction used by these authors and further assume that the fast mode is excited *directly* by the current fluctuation, we can calculate the spectral density of the emitted light. The result is similar to Eq. (2.42) of Laks and Mills. The calculated spectral density correctly predicts the angle dependence of the emission intensity as shown in Fig. 2. However, the calculated emission spectra are much broader than is observed (see Fig. 3).

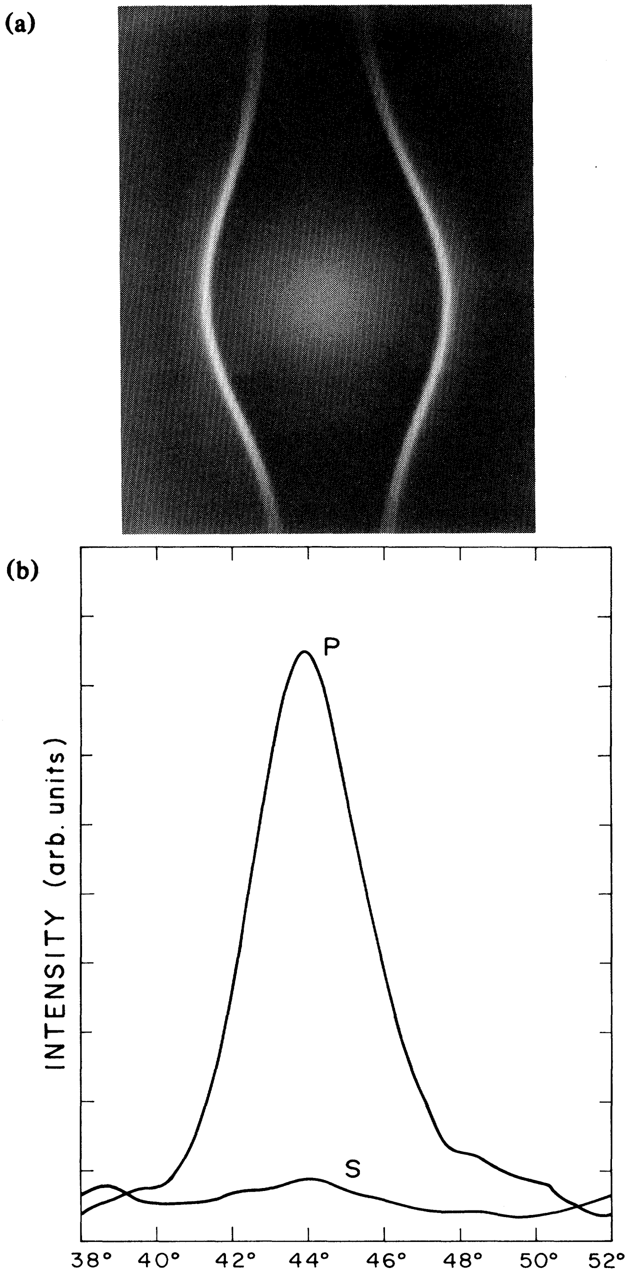

FIG. 2. (a) Light emitted from the tunnel junction through a hemicylindrical prism. The diffuse light seen in the center of the picture is the emission due to residual surface roughness. (b) Angle scan across the light cone of (a), at 5850 Å.

The calculated SPP dispersion curves and lifetimes and the emitted spectra contain the full, complex dielectric functions of both metals.[14] The calculations are based on the assumption that high-frequency inelastic tunneling currents drive the SPP modes. The results can be summarized as a contour plot of spectral

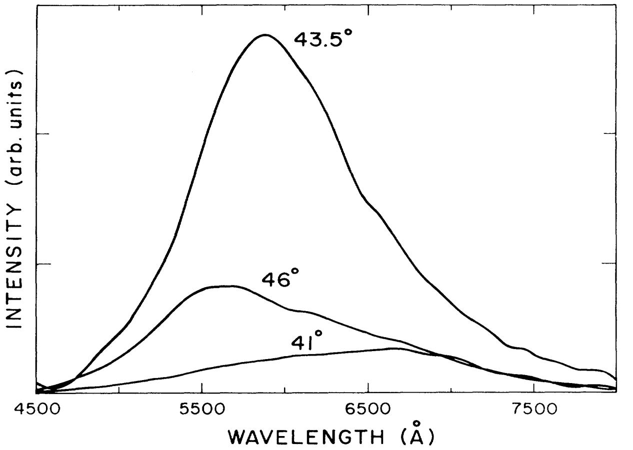

FIG. 3. Spectra taken at three different angles for p-polarized light. The bias voltage was 2.6 V for the highest peak and 2.75 V for the other two spectra.

density in the $(k_{\parallel}, \omega)$ plane. A narrow ridge corresponding to the fast mode lies just to the right of the vacuum light line. The $k_{\parallel}$-vs-ω line for a photon emitted into the prism at 43.4° runs along the crest of this ridge. This reflects the kinematic argument described earlier. In addition there is a second high ridge in the large-$k_{\parallel}$ region, $1\times10^6 \lesssim k_{\parallel} \lesssim 2\times10^6$ cm^{-1}, and between 1.6 and 2.2 eV. This is the frequency region of the peak in Fig. 3. The second ridge corresponds to the slow or junction mode. Although this mode is nonradiative in the simple model, it has an enormous spectral density, in agreement with earlier suggestions that the slow mode is more efficiently excited by tunneling currents than the fast mode.[6,10]

The presence of the slow mode suggests an explanation for the peak in the spectra of Fig. 3. Our junctions emitted weak but detectable s-polarized light indicating the presence of residual roughness in our junctions. In principle, surface roughness can convert slow-mode plasmons into the radiative fast mode. Since the slow mode is much more strongly driven than the fast mode, the scattering from slow to fast mode should dominate the reverse process. The observed spectra result from the net excitation of the fast mode arising both from the direct excitation of the fast mode by tunneling currents and from the conversion of the slow mode. The localization of the spectral density between 1.6 and 2.2 eV causes the narrow peak.

We suggest roughness-mediated mode conversion as a simple way of modifying our model to explain the observed peak in the spectra. Weak evidence for this process is that small variations in the spectra that we observe from junction to junction can be attributed to different amounts of residual roughness. However, we emphasize that the viability of this picture depends on the assumption that the matrix element for the conversion of slow-mode to fast-mode plasmons exceeds the matrix element for the conversion of plasmons of either type to free photons. To our knowledge the relative rates of these processes have not yet been explored either experimentally or theoretically.

Finally, our model entirely neglects the generation of plasmons by hot electrons. It has been shown[7,15] that the fast mode can be excited by hot electrons and a complete theory of light emission should include this process. The hot-electron process could contribute to the broad background underneath the mode-converted peak.

To conclude, we have observed light emission from tunnel junctions through a prism coupler. Both the angle dependence of the emission intensity and the polarization show unequivocally that the light is emitted by the fast mode. The emission spectral shapes, on the other hand, suggest that the dominant channel of excitation for the fast mode is through conversion of the slow mode via surface roughness and not through direct excitation by current fluctuations.

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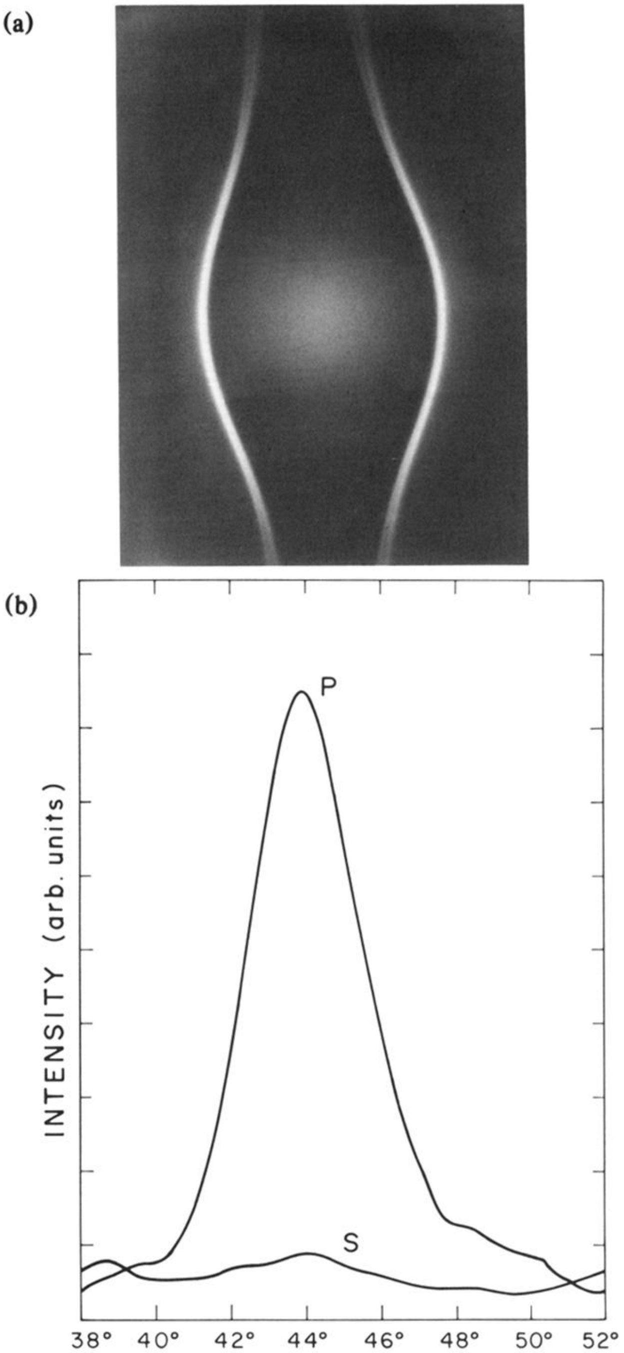

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