tering amplitudes involved in the umklapp processes. As one test case we have examined saturated nitrogen on W(001) which also has $C(2\times 2)$ LEED structure.[10] The results showed a large chemisorption-induced doublet with properties very similar to those presented here for H($C/4$), as the model predicted. A pair of nitrogen difference curves are shown in Fig. 3. The behavior of intensity versus coverage, C, merits mention. Nitrogen is known to adsorb in a rather less ordered manner than hydrogen[10] and we had therefore expected to observe a lower intensity increase[10] than the nearly linear behavior of hydrogen shown in Fig. 2. The intensity was, indeed, found to be concave upwards with zero slope at $C=0$ and fairly well represented by a C^2 dependence over much of the coverage range. We regard the nitrogen observations as strong corroboration for our model.

Many helpful discussions were provided by John Hermanson, and the assistance of the Wisconsin Synchrotron Radiation Center staff was important.

†Research sponsored by the U. S. Air Force Office of Scientific Research, Air Force Systems Command, under Grants No. AFOSR 71-2061 and No. 75-2872. The storage ring is supported by National Science Foundation Grant No. 144-F805.

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Plasma Radiation from Tunnel Junctions*

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(Received 10 November 1975)

Electromagnetic radiation with a spectrum sharply concentrated near the bulk plasma frequency of silver has been observed in emission from Al-Al_2O_3-Ag planar tunnel junctions.

It is well known that metal foils irradiated with beams of energetic electrons can emit electromagnetic radiation, with a spectrum concentrated near the bulk plasma frequency.[1-3] In this Letter we report observation of similar radiation excited by low-energy electrons in planar aluminum–aluminum-oxide–silver tunnel junctions. Although the fundamental mechanisms of photon emission appear similar to those in high-energy experiments, we are now observing them in the "quantum" regime where electron energy is approximately equal to $\hbar\omega_p$. Furthermore, tunnel structures are rather different experimentally, and thus offer new opportunities for studies of plasma oscillations in metals.

The tunnel junctions were made by evaporating, on a glass substrate, an aluminum strip of approximately 750 Å thickness. The aluminum was oxidized by a plasma oxidation technique and a perpendicular strip of silver (thickness approximately 175 Å) was then evaporated across it. The junction area was 1.8×10^{-4} cm^2, and from capacitance measurements we estimate the oxide thickness to be 30 Å. At room temperature the

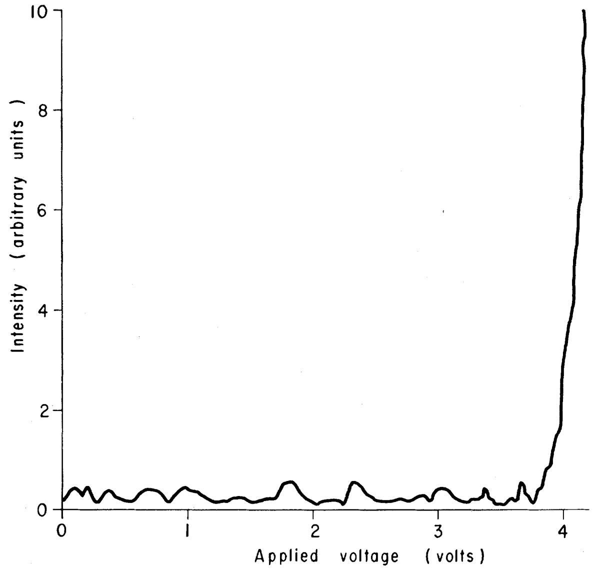

FIG. 1. Intensity at peak wavelength (3230 Å) versus applied voltage, for light emerging at 40° with normal.

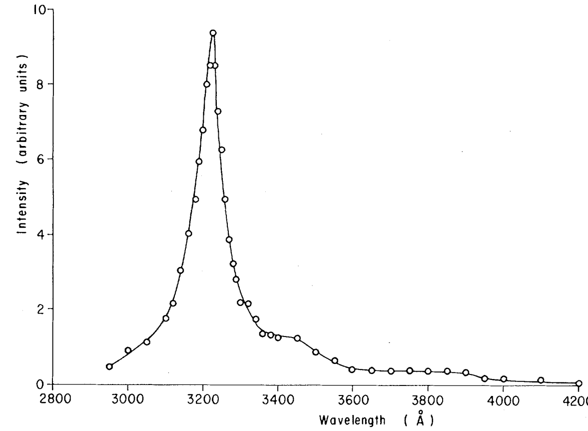

FIG. 2. Intensity versus wavelength at 40° with normal.

junctions tended to break down when applied voltage reached 3 V; however, at 77°K 4 V or slightly more could be applied, and hence measurements were made at this temperature. Detection was by means of an EMI type 9635QB photomultiplier. In most cases the voltage applied to the diode was audiofrequency ac. Use of ac excitation was found to prolong the life of the diode, and also allowed phase-sensitive detection to be used conveniently. However for measurements of intensity versus applied voltage, dc excitation and detection were used. For spectral measurements, the spectral response of the photomultiplier-monochromator combination was calibrated by means of an EOA calibrated quartz-iodine incandescent lamp.

When voltage was applied to the junction with the Al side positive, no radiation was observed up to breakdown voltage. With the opposite bias (electrons moving from Al into Ag) a sharp threshold for radiation emission was observed at a voltage closely corresponding to the 3.82-V bulk-plasma-frequency quantum at 77°K in silver[4] (Fig. 1). The spectrum of the emitted radiation is shown in Fig. 2. This spectrum was made using a Jarrell-Ash 0.25-m ($f/3.5$) monochromator with approximately 20 Å resolution, oriented to accept radiation emerging at an angle of about 40° to the surface normal. The spectral peak at 3230 Å agrees well with the reported 3245-Å plasma wavelength at this temperature.[4] The radiation was primarily p polarized (by a ratio of at least 10:1 at an angle of 40°) as expected from theory.[1,5] The angular distribution of the plasma-frequency radiation, shown in Fig. 3, also agrees in its general features with theory[1,5] and with experimental results with electron beams.[6] The pronounced linear polarization and nonuniform angular distribution of the radiation provide clear evidence that the radiation does not originate from single-particle interband transitions. The radiation originates primarily from the surface of the diode, and not from its edges; this was determined by covering the edges of the sample with opaque ma-

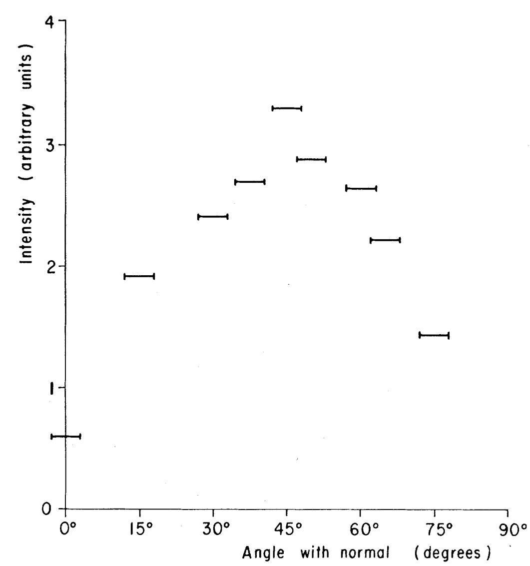

FIG. 3. Intensity versus angle with normal at peak wavelength (3230 Å). Horizontal error bars reflect uncertainty in angle settings.

terial. The maximum power obtained in the plasma-frequency peak (integrated over 2π sr) was approximtely 5×10^{-12} W, at input voltage 4.2 V and input current 60 μA, corresponding to an overall power conversion efficiency of 2×10^{-8}, or one photon per 5×10^{7} electrons. This yield is about 25 times less than would be predicted by direct application of the theory of Ferrell.[1] It is to be expected that the electrons emerging from the insulating barrier are somewhat distributed in velocity space because of collisions with phonons in the insulator. Only the most energetic electrons (those with energy greater than $\hbar\omega_p$) can contribute to the radiation process, which probably accounts for the reduced ratio of emitted photons to electrons. The power conversion efficiency increased very strongly with increasing voltage, but was limited by the diodes' tendency to burn out at around 4 V bias.

The theory of the process by which the kinetic energy of electrons is converted to electromagnetic radiation near the plasma frequency has been studied by many workers. In Ferrell's point of view,[1,7] electrons are considered to excite "radiative" plasmons; in a different but equivalent point of view,[8] one speaks of the "transition radiation" which is to be expected when charged particles cross from one dielectric into another. Although the general features of both theories appear to be applicable to the present circumstances, some differences (other than the obvious one of electron energy) do exist. If one thinks of radiative plasmons, they must now be the oscillations characteristic of the three-layer Al-Ag-air structure, rather than a single thin film of Ag. On the other hand, if one is to use the theory of transition radiation, it should be noted that the first "transition" is from Al (with large negative permittivity) into the silver, while the second transition is replaced by a reflection at the second silver surface back into the metal. An interesting illustration of these differences is the fact that the spectral peak observed in the present experiment is almost perfectly symmetric, in contrast to previous experimental and theoretical work with Ag. The reason may be seen from the theory of Ferrell and Stern[9] where it is shown that the probability of photon emission at the frequency ω is proportional to $|1-\epsilon|^2F(\omega)$, where $\epsilon(\omega)$ is the relative dielectric permittivity of silver and $F(\omega)$ is approximately Lorentzian. The factor $|1-\epsilon|$ originates from the particles' transitions from a medium with unit permittivity into the dielectric and back out again. In silver the function $|1-\epsilon|$ has a sharp minimum at a frequency just above the plasma frequency, and in experiments with free-standing foils this distorts the Lorentzian line shape by cutting it off on the high-frequency side. In the present case, however, the single transition is from aluminum into silver, and consequently the factor $|1-\epsilon|$ must be replaced by $|\epsilon_{Al}-\epsilon|$, where ϵ_{Al} is the relative permittivity of Al. Since $|\epsilon_{Al}-\epsilon|$ does not have a minimum near ω_p, the resulting line is not distorted.

The relatively large light output power and high resolution available with this experimental technique suggest that it may be useful for new studies of plasma oscillations in metals. The 20-Å resolution obtained in our initial spectral measurements is about 2.5 times higher than the resolution reported in electron-beam experiments.[6] Experiments with higher resolution should be possible by increasing the emitted power, perhaps by increasing current or voltage or by using many diodes side by side. The 10:1 polarization ratio appears to be higher than has been observed previously, and this may indicate that extraneous effects, such as bremsstrahlung due to scattering, are less important than in the high-energy method. The evaporated-layer structure also allows fabrication of shapes more complex than simple plane films, perhaps with scale not many times larger than wavelength. Such structures could support plasma oscillations other than the simple modes of a thin film. There may also be possibilities for incoherent or coherent radiation sources, if the overall efficiency can be improved. In this connection, one may note that the conversion of "hot" injected electrons into plasmons (not necessarily radiative) is expected to be greater than 50% when the electron kinetic energy is larger than $\hbar\omega_p$.[10] The inefficient step is presumably the conversion of plasmons to electromagnetic radiation. If a structure can be found which will enhance this conversion, considerably greater conversion efficiency might be obtainable.

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*Research sponsored by the Joint Services Electronics Program Contract No. F44620-71-C-0087, and by the U. S. Army Research Office, Grant No. DAHC04-73-C-0026.

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Josephson Oscillation of a Moving Vortex Lattice

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Experimental evidence is presented for a supercurrent oscillation arising from vortex motion in the flux-flow regime of superconducting films with periodically modulated thickness. An essential condition for detecting the rf electric field associated with the oscillation is matching of the vortex lattice to the periodic pinning structure represented by the thickness modulation.

This Letter reports the observation of radiofrequency (rf) electric fields in the flux-flow regime of type-II superconducting films with periodically modulated thickness when vortex motion is driven by a dc transport current. These oscillating voltages are a manifestation of a Josephson-like supercurrent oscillation arising from coherent vortex motion in the one-dimensional periodic pinning potential represented by the thickness modulation.[1] Evidence for the oscillation is found when the value of the transverse magnetic field $H \simeq B$ corresponds to matching of the vortex lattice to the periodic film structure.

Several years ago, Kulik[2] and Schwartz[3] suggested that there is a close analogy between the flux-flow state in type-II superconductors and the ac Josephson effect in superconducting weak links. In fact, a moving vortex lattice can be thought of as a supercurrent density distribution oscillating both in space and time in a way very similar to that sometimes observed in weak links in connection with the ac Josephson effect.[4] According to this picture, one would expect the existence of electromagnetic radiation from type-II superconductors in the flux-flow regime.[2,3]

As pointed out by Meincke,[5] however, the dramatic mismatch between the flux-flow velocity (or phase velocity of the supercurrent pattern) and the phase velocity of the electromagnetic field almost excludes the possibility of detecting ac Josephson effects in type-II superconductors. Meincke's argument, however, is only valid for uniform motion of an extended vortex lattice. Actually, by considering flux flow in the presence of pinning, Schmid and Hauger[6] have shown that the pinning potential introduces the necessary mechanism for coupling electromagnetic fields to the supercurrent oscillations. This coupling can be significant only when the effect of pinning results in a sufficiently coherent modulation of the vortex velocity. In this case the corresponding modulation of the supercurrent density distribution leads to a net supercurrent oscillation which can therefore interact with the electromagnetic field. This interaction was first demonstrated experimentally for weak random pinning by Fiory[7] and recently for a periodic pinning structure by Martinoli *et al.*,[8] who observed quantum-interference phenomena when the flux-flow state was driven by superimposed dc and rf currents.

At this point, the problem of the direct detection of the supercurrent oscillation associated with the moving lattice arises in a quite natural way. In this connection, we note that Clem[9] predicts the existence of characteristic structures, related to the oscillation, in the noise power spectrum. Such structures, however, were not observed by Fiory[7] for flux flow in a random pinning potential. In this respect our modulated