view, see e.g., B. Shapiro, "Localization versus Percolation," to appear in: "Percolation Structures and Processes," edited by G. Deutscher, R. Zallen, and J. Adler (Hilger, Bristol, to be published).

[4]B. Shapiro and E. Abrahams, Phys. Rev. B 24, 4025 (1981).

[5]S. Hikami, Phys. Rev. B 24, 2671 (1981).

[6]J. P. Straley, J. Phys. C 10, 3009 (1977).

[7]R. Abou-Chacra, P. W. Anderson, and D. J. Thouless, J. Phys. C 6, 1734 (1973); see also H. Kunz and B. Souillard, in *Disordered Systems and Localization*, edited by C. Castellani, C. DiCastro, and L. Peliti (Springer-Verlag, 1981); A. B. Harris, Phys. Rev. Lett. 49, 296 (1982).

[8]M. Jonson and S. M. Girvin, Phys. Rev. Lett. 43, 1447 (1979); S. M. Girvin and M. Jonson, Phys. Rev. B 22, 3583 (1980).

[9]P. W. Anderson, Phys. Rev. 109, 1492 (1958).

[10]P. W. Anderson, D. J. Thouless, E. Abrahams, and D. S. Fisher, Phys. Rev. B 22, 3519 (1980).

[11]P. W. Anderson, Phys. Rev. B 23, 4828 (1981).

[12]M. Azbel, Phys. Rev. B 25, 849 (1982).

[13]B. Shapiro, Phys. Rev. Lett. 48, 823 (1982).

[14]For example, S. Chandrasekhar, Rev. Mod. Phys. 15, 1 (1943).

[15]R. Landauer, Philos. Mag. 21, 863 (1970).

[16]Strictly speaking, the Landauer formula is valid only for a single-channel scatterer. In a multichannel case there seems to be no simple general relation between the resistance of a scatterer and its S matrix [see D. S. Langreth and E. Abrahams, Phys. Rev. B 24, 2978 (1981)]. It can be shown, however, that for the simple multichannel structure in Fig. 2 (i.e. one channel on the left, q channels on the right), and provided that $\tilde{\epsilon} \ll 1$, Landauer formula does hold approximately, i.e., the resistance $\tilde{\rho}$ of the whole array is $\tilde{\rho} = (1/\tilde{\epsilon}) + O(1)$.

Light Emission from Electron-Injector Structures

T. N. Theis, J. R. Kirtley, D. J. DiMaria, and D. W. Dong

IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

(Received 14 December 1982)

Surface-plasmon-polariton–mediated luminescence is observed when electrons are injected into thin Al films from the conduction band of SiO_2. These electron-injector structures are strikingly similar to light-emitting tunnel junctions, although tunneling can be ruled out as the driving mechanism. The emission arises from the energy relaxation of the steady-state hot-electron distribution which exists in the metal under continuous current injection. The same mechanism must explain much of the luminescence from tunnel junctions.

PACS numbers: 73.40.Ns, 71.36.+c, 73.40.Gk, 78.60.Fi

Since the seminal papers of Lambe and McCarthy,[1,2] it has been widely accepted that light emission from metal-insulator-metal (MIM) tunnel junctions results from a two-stage process. First, an electron tunnels inelastically, losing its energy to a collective excitation of the junction. Second, in the presence of surface roughness, this excitation may radiate. Since the energy loss occurs in the insulating region of the junction,[3,4] inelastic tunneling should most efficiently excite electromagnetic modes with large energy density in this region. Theoretical attention[4,5] was therefore initially focused on the "slow wave" or junction mode,[6] with fields concentrated between the metal electrodes. However, radiation from electrodes consisting of many small metal balls[7-9] has been shown to be mediated by localized plasmons.[9-11] More recently light emission has been demonstrated via the "fast" surface-plasmon polariton, which has a maximum energy density at the outer electrode surface.[12-15] To explain the efficiency with which the fast mode is excited, Laks and Mills[16] proposed a phenomenological model in which the inelastic-tunneling current fluctuations extend into the metal electrodes on both sides of the insulating junction. However, the excitation efficiency appears to be much higher than predicted by this theory.[14] This and several other puzzling results, discussed at length in Refs. 14 and 17, have suggested the importance of an alternative excitation mechanism, the injection of hot electrons into the metal by *elastic* tunneling.

If this mechanism is correct, it should not matter *how* the electrons are injected, as long as they enter the metal with energies several electronvolts in excess of the Fermi energy. Here we report the observation of surface-plasmon-polariton–mediated light emission when electrons are injected from the conduction band of SiO_2 into

a thin Al film. The SiO_2 layer is sufficiently thick (50 nm) that no direct tunneling into the metal, elastic or inelastic, is possible. Nevertheless, the distinguishing features of light emission from tunnel junctions are reproduced. A similar process when the current injection is by elastic tunneling is strongly implied.

The devices used in these experiments are called electron-injector structures.[18,19] Figure 1 shows the energy-band diagram of such a device under positive bias. It is a metal-oxide-semiconductor sandwich, with a layer of silicon-rich oxide (Si-rich SiO_2) between the stochiometric oxide (SiO_2) and the degenerately doped n-type Si substrate. The Si-rich material is two phase, containing many tiny ($<\sim 5$ nm) inclusions or islands of Si in an SiO_2 matrix.[20] Conduction through this layer is predominantly by direct tunneling from Si island to Si island. Electrons subsequently enter the SiO_2 conduction band at thermal energies by Fowler-Nordheim tunneling. Local enhancement of the electric field near each Si island allows the tunneling to proceed at comparatively low bias voltages, yet the islands are packed densely enough that the fields and currents in the bulk of the SiO_2 are laterally uniform.[18]

Once in the SiO_2 conduction band, electrons are quickly swept to the opposite interface. Injected into the metal electrode, they rapidly lose energy by electron-electron and electron-phonon interactions on a time scale of $\sim 10^{-15}$ sec. In contrast, the generation of a surface-plasmon polariton via an electronic collision with the outer wall of the metal electrode, as shown in Fig. 1, requires $\sim 10^{-12}$ sec.[21] The relatively weak plasmon loss will therefore give rise to light emission without greatly affecting the steady-state energy distribution of hot electrons produced by continuous current injection.

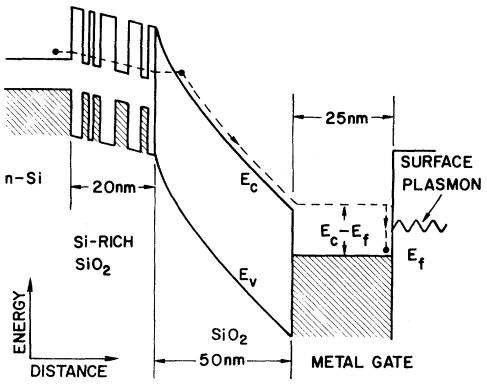

FIG. 1. Energy-band diagram of a positively biased electron-injector structure.

In order to unequivocally demonstrate this luminescence mechanism, we have fabricated electron-injector structures on periodic corrugated gratings. The gratings were ion milled into Si substrates as described in Ref. 14. Successive layers of Si-rich SiO_2 and stochiometric SiO_2 were then formed by chemical vapor deposition (Refs. 18 and 20), preserving the corrugated pattern as shown in Fig. 2(a). Following a 1000-C N_2 anneal, circular Al electrodes, ~ 0.017 cm^2 in area and 25 nm thick, were evaporated through a mask. This was followed by a forming gas anneal at 400 C for 20 min.

The devices could typically be biased at 20–25 V with time-averaged current densities of about 10^{-2} A/cm^2. As current was passed through the devices, charge was trapped in the oxide, lowering the field at the Si-rich SiO_2–SiO_2 interface. The bias voltage, therefore, had to be gradually increased to maintain a constant current. The emitted light was collected by a spherical mirror, focused at the input of a single pass monochrom-

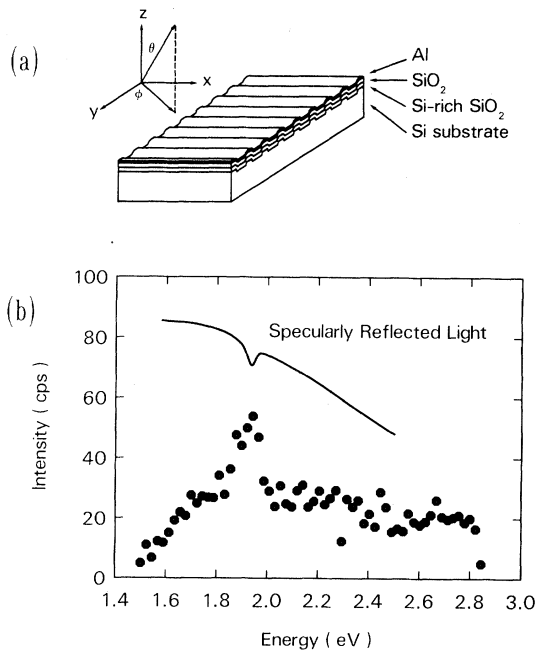

FIG. 2. (a) Schematic drawing of an electron injector fabricated on a substrate with a corrugated grating surface. Luminescence spectra were obtained in the $\varphi = 0$ plane as a function θ. (b) Luminescence spectrum from the sample at $\theta = 13°$ (dots). The sharp emission peak at 1.95 eV corresponds well to the surface-plasmon-polariton dip in the specular reflection for light incident at $\theta = -13°$, shown by the solid curve.

ator, and detected by photon counting techniques. An aperture in front of the collecting mirror allowed angular resolution of the spectra.

Referring to the coordinate system of Fig. 2(a) light was collected in the plane defined by $\varphi = 0$, while θ could be varied. The resonance condition for coupling of a surface-plasmon polariton of wave number q to light by a grating of periodicity a then takes the simple form

$$k_{\parallel} \equiv (\omega/c)\sin\theta = q \pm n(2\pi/a), \quad n = 1, 2, \ldots, \qquad (1)$$

where $k_{\parallel}$ is the wave number parallel to the surface. For a fixed value of θ, Eq. (1) is satisfied only at discrete energies, resulting in characteristic, angle-tunable peaks in the emission spectrum. One such peak is evident in the spectrum in Fig. 2(b), obtained at $\theta = 13°$ from a device fabricated on a grating of 815-nm period and 36-nm amplitude. The bias voltage was adjusted to maintain a constant current of 100 μA. Also included in the figure is a plot of the specularly reflected light from a collimated white light source directed at the sample at an angle of $\theta = -13°$ and detected in the same geometry as the emitted light. The reflectivity dip corresponds to the satisfaction of the resonance condition, Eq. (1), and the conversion of incident photons to surface-plasmon polaritons. The exact match in energy between this dip and the emission peak shows that the same mode, the "fast" surface-plasmon polariton,[22] is involved in the emission. The dispersion closely follows the light line, and the peak position is well predicted by Eq. (1) with $n = 1$. Luminescence from tunnel junctions fabricated on corrugated gratings is mediated by the same mode.[12-15]

The emission peak sits on a continuum background. A calculation following the method of Laks and Mills[16] indicates that about half of this background is mediated by surface-plasmon polaritons. Much of the integrated intensity is not beneath the sharp peak because surface modes are strongly damped on Al compared with, for example, Ag. The remainder of the background is apparently due to luminescence from the oxide layer, as discussed below.

If the periodic grating is replaced by random roughness with transverse correlations of widely varying length, the result will be a broadband emission spectrum. Smooth substrates were roughened by deposition of a 250-nm-thick layer of n-degenerate polycrystalline Si. The roughness of this layer was enhanced by thermally growing and then chemically stripping 50 nm of oxide. Injector structures were then fabricated on the substrates as before. In Fig. 3 the spectrum from a charge injector fabricated on a smooth substrate is compared with that from an electrically identical device fabricated simultaneously on a rough substrate. The bias voltage was a pulsed square wave, driving a time-averaged current of 10 μA. The pulse width was 1 msec with a low duty cycle of 1:20 which helped to discriminate against detector dark counts. The spectra have been normalized for the relative throughput of the spectrometer and detection system, with the throughput at 3.5 eV set arbitrarily to 1.

The radiation from the nominally smooth forward biased sample appears to be dominated by luminescence from the bulk of the oxide as reported by others.[23,24] As would be expected in that case, a nearly identical spectrum (not shown) is obtained if the sample is reverse biased so that electrons flow from the metal to the substrate. By contrast, the roughened sample has a dramatically different spectrum in forward (but not in reverse) bias. The increase in brightness with surface roughness is evidence that the additional light emission, the difference spectrum of Fig. 3, is mediated by surface-plasmon polaritons. This spectrum is peaked in the visible and decreases linearly toward a high-energy cutoff. It thus strongly resembles the luminescence spectrum of a tunnel junction fabricated on a roughened substrate.[1]

For tunnel junctions the cutoff has been explained as a consequence of the inelastic tunneling model,[1,10] but the difference spectrum of Fig. 3 shows that hot-electron injection can also produce this feature. We propose a simple explanation based on the fact that the average injected electron which generates a surface plasmon has already lost energy through other channels. With neglect of any angular dependence of the initial

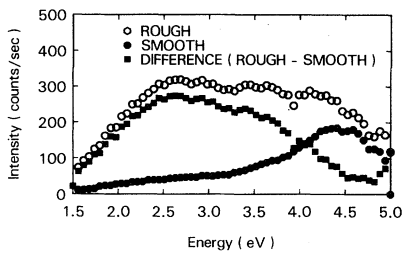

FIG. 3. Luminescence spectra from rough and smooth electron-injector structures. The difference spectrum represents the surface-plasmon-polariton–mediated emission from the roughened sample.

electronic state occupation function, $f(E)$, in the metal, the number of photons emitted with frequency ν within an interval $d\nu$ can be written as

$$L(\nu) = \int_0^\infty f(E)[1 - f(E - h\nu)]P(\nu, E)dE, \qquad (2)$$

where $P(\nu, E)$ is a slowly varying function of ν and E involving the density of surface modes, and the surface-plasmon-polariton excitation and radiation probabilities. We assume $f(E) = f_t(E) + \Delta f(E)$, where $f_t(E)$ is the thermal Fermi distribution, and $\Delta f(E) \ll 1$. If the plasmon loss channel were strong enough to dominate electron-electron and electron-phonon losses, the appropriate hot-electron distribution would be a delta function, $\Delta f(E) \sim \delta(E - E_i)$, at the injection energy, E_i. Since $P(\nu, E)$ depends weakly on energy and since $E_i - E_f \gg k_B T$, this would result in an abrupt, step-function cutoff, $L(\nu) \sim P(\nu)\Theta(E_i - E_f - h\nu)$. However, because surface-plasmon-polariton generation is a weak channel for energy loss it is more accurate to assume a relaxed hot-electron distribution $\Delta f(E) \sim \Theta(E_i - E)$ resulting in the linear cutoff which is in fact observed: $L(\nu) \sim P(\nu)(E_i - E_f - h\nu)$.

The injection is indeed approximately monoenergetic as assumed above. The minimum energy with which electrons enter the metal corresponds to the potential step, $E_c - E_f = 3.5$ eV, between the bottom of the SiO_2 conduction band and the Al Fermi level.[25] From the cutoff at 4.5 eV we deduce that the electrons are injected with average energies about 1 eV above E_c. We emphasize that the cutoff cannot be associated with a lack of small-scale roughness for radiative coupling at high energies, since it is observed to move to much higher energies as the field in the SiO_2 is increased. This spectroscopic evidence for strong electric field heating of conduction-band electrons is of great interest in understanding dielectric breakdown in SiO_2, and a report of initial results is being prepared.[26]

The difference spectrum of Fig. 3 yields a total luminescent quantum efficiency of about 10^{-6} photons/electron, somewhat lower than the best values reported for tunnel junctions with Ag or Au electrodes.[1,2,8,9] However, the radiative efficiencies of surface-plasmon polaritons are much higher for Ag or Au than for the Al electrodes of our injectors. The model of Laks and Mills,[5,16] which gives a very good account of the radiative properties of MIM tunnel junctions,[14] predicts that injectors fabricated with Ag electrodes should be about 100 times brighter. The extrapolated efficiency of 10^{-4} is then easily comparable to the best tunnel-junction values. This underlines our principle conclusion, that hot-electron injection (by elastic tunneling) must be an important driving mechanism for luminescence from tunnel junctions.

We gratefully acknowledge the assistance of J. A. Tornello and J. A. Calise in sample preparation, R. Bennett for reactive ion etching, and B. Eck for ion milling of the gratings used in this work, and C. F. Aliotta for characterizing the samples with scanning electron microscopy. We thank A. B. Fowler, D. L. Mills, B. Laks, and F. Stern for helpful discussions.

[1]J. Lambe and S. L. McCarthy, Phys. Rev. Lett. 37, 923 (1976).

[2]S. L. McCarthy and J. Lambe, Appl. Phys. Lett. 30, 427 (1977), and 33, 858 (1978).

[3]K. L. Ngai, E. N. Economou, and Morrel H. Cohen, Phys. Rev. Lett. 22, 1375 (1969).

[4]L. C. Davis, Phys. Rev. B 16, 2482 (1977).

[5]B. Laks and D. L. Mills, Phys. Rev. B 20, 4962 (1979), and 21, 5175 (1980).

[6]J. C. Swihart, J. Appl. Phys. 32, 461 (1961).

[7]S. L. McCarthy and John Lambe, Appl. Phys. Lett. 33, 858 (1978).

[8]P. K. Hansma and H. P. Broida, Appl. Phys. Lett. 32, 545 (1978).

[9]A. Adams, J. C. Wyss, and P. K. Hansma, Phys. Rev. Lett. 42, 912 (1979).

[10]Daniel Hone, B. Mühlschlegel, and D. J. Scalapino, Appl. Phys. Lett. 33, 203 (1978).

[11]R. W. Rendell and D. J. Scalapino, Phys. Rev. B 24, 3276 (1981).

[12]J. R. Kirtley, T. N. Theis, and J. C. Tsang, Appl. Phys. Lett. 37, 435 (1980).

[13]N. Kroo, Zs. Szentirmay, and J. Felszerfalvi, Phys. Lett. 81A, 399 (1981).

[14]John Kirtley, T. N. Theis, and J. C. Tsang, Phys. Rev. B 24, 5650 (1981).

[15]N. Kroo, Zs. Szentirmay, and J. Felszerfalvi, Phys. Lett. 86A, 445 (1981).

[16]Bernardo Laks and D. L. Mills, Phys. Rev. B 22, 5723 (1980).

[17]J. R. Kirtley, T. N. Theis, J. C. Tsang, and D. J. DiMaria, Phys. Rev. B, to be published.

[18]D. J. DiMaria, R. Ghez, and D. W. Dong, J. Appl. Phys. 51, 4830 (1980).

[19]D. J. DiMaria, K. M. DeMeyer, C. M. Serrano, and D. W. Dong, J. Appl. Phys. 52, 4825 (1981).

[20]D. J. DiMaria, in *The Physics of MOS Insulators*, edited by G. Lucovsky, S. T. Pantelides, and F. L. Galeener (Pergamon, New York, 1980), pp.1–18.

[21]J. R. Kirtley, unpublished.

[22]For a complete discussion of surface-plasmon modes in various planar thin-film geometries, see E. N. Economou, Phys. Rev. 182, 539 (1969).

[23]P. Solomon and N. Klein, J. Appl. Phys. 47, 1023 (1976).
[24]C. Falcony, Doctoral dissertation, Lehigh University, 1980 (unpublished).
[25]P. M. Solomon and D. J. DiMaria, J. Appl. Phys. 52, 5867 (1981).
[26]T. N. Theis, J. R. Kirtley, D. J. DiMaria, and D. W. Dong, unpublished.

Magneto-Polarons in a Two-Dimensional Electron Inversion Layer on InSb

M. Horst, U. Merkt, and J. P. Kotthaus
Institut für Angewandte Physik, Universität Hamburg, D-2000 Hamburg 36, West Germany

(Received 22 October 1982)

In electron inversion layers on InSb the cylotron resonance energies and linewidths are found to exhibit a marked discontinuity in the vicinity of the bulk longitudinal-optical-phonon energy. These features are attributed to resonant electron-phonon interaction in the two-dimensional electron system. The experimentally observed mass discontinuity indicates that the electron–optical-phonon interaction in a two-dimensionally confined electron system is enhanced in comparison to the three-dimensional case.

PACS numbers: 73.40.Qv, 71.38.+i, 78.20.Ls

Here we report on the observation of magneto-polaron effects in a two-dimensional electron system (2DES) that is created by field effect[1] at the semiconductor-oxide interface in a metal-oxide-semiconductor (MOS) structure on p-InSb. In our experiments we investigate the frequency dependence of the cyclotron resonance (CR) of inversion-layer electrons at discrete laser energies below and above the reststrahlen region. Resonant electron-phonon interaction is observed to cause discontinuities in the cyclotron energies and linewidths of Landau transitions in different electric subbands as the laser energy is varied from below to above the longitudinal optical (LO) phonon energy. Our investigations constitute the first clear experimental evidence that the two-dimensional confinement of the electron system causes a significant enhancement of the electron–optical-phonon interaction.

The nature of the electron–optical-phonon coupling in systems of reduced dimensionality in polar semiconducting materials has recently attracted much theoretical interest[2,3] and a variety of aspects of the surface polaron problem have been pointed out. An electron near the surface of a polar material not only couples to bulk LO phonons, but also may interact with surface optical phonons and purely two-dimensional optical-phonon modes. It has been argued that the presence of the interface makes it possible for phonons with arbitrary wave vectors perpendicular to the surface to participate in the interaction process.[2] This may alter the self-energy correction as compared to the bulk case. Because of the complete quantization of a two-dimensional electron gas in the presence of a magnetic field, the resonant interaction of Landau electrons with LO phonons is also expected to be much sharper than in the bulk.

In inversion layers of MOS structures the electron motion normal to the surface is quantized in electric subbands E_i as a result of the surface electric field, while the electrons are free to move parallel to the surface.[1] If a magnetic field B is applied perpendicular to the surface the parallel motion becomes quantized in Landau levels n. With neglect of electron spin, the energy spectrum is given by $E_{i,n}=E_i+\hbar\omega_{i,n}(n+\frac{1}{2})$ where $\omega_{i,n}=eB/m_{i,n}$ and $m_{i,n}$ is the frequency-dependent cyclotron mass of the n to $n+1$ Landau transition in the subband i.

Since CR in n-InSb has successfully been used to study volume magneto-polarons,[4,5] and surface CR in inversion layers on InSb has been investigated previously[6,7] to determine CR masses in their dependence on electric subband index and inversion electron density, CR seems best suited also to obtain information on the electron–optical-phonon interaction in a 2DES. For such experiments it is vital to fabricate MOS structures with very high inversion-layer mobilities to be able to extract the relatively small polaron effects. The substrates of our MOS capacitors are Ge-doped ($N_A \simeq 10^{14}$ cm^{-3}) p-type InSb(111) platelets with a typically 400-nm-thick SiO_2 gate insulator[8] and a semitransparent NiCr gate contact.

