(NASA-CR-169904) CCLLABORATIVE RESEARCH IN TUNNELING AND FIELD EMISSICN PUMPED SURFACE WAVE LOCAL OSCILLATORS AND AMPLIFIERS FOR INFRARED AND SUBMILLIMETER WAVELENGTHS UNDER DIRECTOR'S DISCRETIONARY FUND (California

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COLLEGE OF ENGINEERING
ELECTRONICS RESEARCH LABORATORY

BERKELEY, CALIFORNIA 94720

Collaborative Research in Tunneling and Field Emission Pumped Surface Wave Local Oscillators and Amplifiers for Infrared and Submillimeter Wavelengths under Director's Discretionary Fund

Professor T.K. Gustafson

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Statement of Purpose:

The goal of the project was to work towards the development of surface wave sources for the infrared and sub-millimeter portion of the spectrum. These were to be based upon electron pumping by tunneling electrons in metal-barrier-metal or metal-barrier-semiconductor devices. The contract provided for the purchase of a spectrum analyzer to be utilized for fundamental investigations of tunneling phenomena and the coupling of radiation to tunneling junctions. The research assistants were supported by N.S.F. grant No. ECS-7923877 and the results will be reported there as well.

Results:

Three things have been accomplished with support from this grant. We have first of all calculated the propagation characteristics of surface electro-magnetic modes in metal-insulator-p^{++} semiconductor structures as a function of frequency. Secondly, we have formulated a simple model for the gain process based upon Tucker's [1] formalism and have utilized this to estimate what low frequency gain might be expected from such structures. And thirdly, we have addressed the question of gain from a more fundamental viewpoint using the method of Lasher and Stern. [2]

The band structure of the junctions which have been of interest is shown in Fig. (1). To the left, the metal is indicated with a Fermi level E_{FM} and work function V_a. This is assumed separated from the semiconductor by a thin barrier ($x_0 \approx 10\text{Å}$) as shown. The semiconductor is assumed p^{++} with valence band edge E_v and conduction band edge E_c. E_{FS} is the Fermi level and V_s the work function.

Since both the metal and the semiconductor, in the frequency range of interest, have negative real parts for their dielectric coefficients, this structure supports a confined TM mode. This particular mode couples to the tunneling current and can be amplified if conditions are right. This is true if the junction structure is such that absorption is inhibited. This in principle is possible in the metal-insulator-heavily doped semiconductor. Considering Fig. (1), there is the possibility of both stimulated emission and absorption as indicated. However, the p^{++} structure allows the emission to dominate over a bias range of the band-gap.

We have estimated the gain possible by using a simple result of the stationary state model for tunneling.(3) This has shown that the gain α is given by

$$\alpha = - \frac{4dS}{L_z W \varepsilon_0 c} \left. \frac{dI}{dV} \right|_{V_B} = + \frac{\hbar\omega(R/L_z)}{P} \tag{1}$$

where R is the net emission rate (per sec.) and P is the power flowing in the guided mode. In this expression $d \equiv x_0$, is the barrier thickness, L_z the propagation length of the mode: W is the width of the junction and S is the slowing factor ($= \frac{c}{v_g}$ where v_g is the group velocity) of the mode which propagates in the junction device. For numerical estimates of gain, we use $d = 10\text{Å}$, $W = L_z = 10^{-4}$ cm (1 μm) and $S \approx 200$. Values of the negative resistance available are presently unclear. 10^{-6} mhos has been obtained by Esaki and Stiles (4) and it is possible that with further development a value of 10^{-3} mhos or higher might be acheived. Such chosen values give an estimate of $\alpha \approx 4 \times 10^3$ cm^{-1} but imply current densities of the order of 10^5 cm^{-2} which is quite high. The most questionable parameters assumed are the values of S and dI/dV.

From a simple analysis extending the Roosbroeck Schockley relation,(2) the spectral rate of emission γ_s is given by

$$\gamma_s = \frac{1}{e^{(\hbar\omega - eV_B)/kT}-1} \frac{e}{\hbar\omega} \frac{\beta d}{\pi\varepsilon_0} d\beta \; I(V_B - \hbar\omega/e) \qquad (2)$$

where β is the propagation constant of the guided mode. Assuming $\beta = S\omega$, and the numbers used previously and

$$\omega \equiv \frac{1}{2} \times 10^{14} \text{ (rad/sec)},\; I(eV_B - \hbar\omega) \cong 10^{-3} \text{ amps},$$

one obtains $\gamma_s \cong 10^{13}$ photons/sec for a bandwidth of 10%. This corresponds to a radiated power of approximately 10^{-7} watts.

This simple analysis, although highly intuitive neglects any effects due to the spreading of the field into the semiconductor or the metal. It has thus been essential to formulate the problem in a more rigorous manner. The net stimulated transition rate R has been calculated as a function of frequency using the method of Lasher and Stern.(2) The rate is given by

$$R = \frac{2L_x^2 L_y}{(2\pi)^2} \int d^3k_i \; \delta^{(2)}(\Delta k_{11}) \int d^3k_f \; |M_{fi}|^2 \; [(\delta(E_f - \hbar\omega - E_i)$$

$$- \delta(E_f + \hbar\omega - E_i))(f_M(E_i - E_{FM}) - f_s(E_f - E_{FS}))] \qquad (3)$$

where L_x and L_y are the normalization lengths of the electronic wave functions in the x and y-directions, respectively. f_m and f_s are the Fermi Dirac distribution functions for the metal and the valence band of the semiconductor; Δk_{11}, the transverse (in the plane of the junction) wavevector difference between initial and final states; and d^3k_i, d^3k_f the initial and final state elements of volume in k-space. The energies E_f and E_i satisfy $E_i = k_i^2/2m_o$ and $E_f - E_v = -k_f^2/2m_h$ where m_o is the electron mass in the metal and m_h is the hole mass in the semiconductor.

The matrix element, $M_{if} = \langle E_f | \frac{-e}{2m} (A.p + p.A) | E_i \rangle$, is obtained from the wavefunctions of Duke, [5] and the guage $A = E_x/(i\omega)$, E_x being the infrared electric field across the barrier. Assuming E_x to be slowly varying over the barrier thickness, neglecting the plasmon and also assuming that only the field within the barrier contributes to the matrix element,

$$|M_{if}| = \frac{2eE_x}{m\omega L_x}\frac{\hbar\alpha_i\alpha(\Gamma_i + \Gamma_f)}{(\alpha_i^2 + \Gamma_i^2)^{1/2}(\alpha_f^2 + \Gamma_f^2)^{1/2}}\frac{\exp(-\Gamma_i x_o) - \exp(-\Gamma_f x_o)}{\Gamma_f - \Gamma_i} \tag{4}$$

where

$$\alpha_i = \left(\frac{2mE_{ix}}{\hbar^2}\right)^{1/2} \tag{5}$$

$$\alpha_f = \left[\frac{2m}{\hbar^2}(E_v - E_{fx})\right]^{1/2} \tag{6}$$

$$\Gamma_i = \left[\frac{2m}{\hbar^2}(V_a + E_{FM} - E_{ix})\right]^{1/2} \tag{7}$$

$$\Gamma_f = \left[\frac{2m}{\hbar^2}(V_s + E_{FS} - E_{fx})\right]^{1/2} \tag{8}$$

and E_{ix} and E_{fx} are $E_i - k_{i||}^2/2m_o$ and $E_f - k_{f||}^2/2m_h$ where $k_{i||}$ and $k_{f||}$ are the initial and final momenta parallel to the junction plane. For m and m_h we have used the free electron mass m_o. For emission, for V_a and V_s above, we have used the values $V_a = e\phi - (eV-\hbar\omega)/2$ and $V_s = e\phi + (eV-\hbar\omega)/2$.(3) Since $E_{FS} = E_{FM} - eV$ and $E_{fx} = E_{ix} - \hbar\omega$ this makes $\Gamma_i = \Gamma_f$ and Eq. (4) simplifies for numerical integration. For absorption $\hbar\omega$ becomes $-\hbar\omega$.

A test of the validity of such a tunneling matrix element for practical junctions at high frequencies is important and is presently being investigated through high frequency mixing. The i.f. frequency is expected to be in the 20 GHz region and should be detectable with the spectrum analyzer purchased for that purpose.

For appreciable gain to occur, the plasmon mode must be confined to the insulator region as the electron state overlap is significant only there and as a consequence, the stimulated emission. From Eqs. (1) and

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(3) a useful definition of the confinement is $C = \frac{1}{2}\sqrt{\frac{\varepsilon}{\mu_0}} \int E_x^2\, x_0 \, dy/P$. For a well confined mode this is equal to the ratio of the speed of light in the insulating layer to the energy velocity, but it decreases below this value as the fields spread into the metal and semiconductor.

The characteristics of this confinement factor, and hence the frequency dependence of the gain, has required a solution of the dispersion relation for the mode characteristics.

The x-component of the antisymmetric plasmon electric held is of the form

$$R_i\{E_x(x)e^{i(\beta z-\omega t)}\}$$

where $E_x(x) = Ae^{\gamma_m x}$, $x<0$ (9a)

$$E_x(x) = Be^{\gamma_b x} + Ce^{-\gamma_b x}, \quad 0\le x\le x_0 \tag{9b}$$

$$E_x(x) = De^{-\gamma_s x}, \quad x>x_0 \tag{9c}$$

The transverse propagation constants γ_s, γ_b, γ_m are given by $\gamma = [\beta^2 - \omega^2\mu_0\varepsilon]^{1/2}$ where $Re(\beta) > 0$ and ε_m, ε_b, ε_s are the dielectric constants in the respective regions shown in Fig. (1). They are taken to be $\varepsilon_m(\omega) = \varepsilon_m(1-\omega_m^2/(\omega^2+i\omega/\zeta_m))$, $\varepsilon_I = \varepsilon_b$ and $\varepsilon_s(\omega) = \varepsilon_\infty(1-\omega_s^2/(\omega^2+i\omega/\zeta_s))$, where ζ_s, ω_s, ζ_m, ω_m are the relaxation times and plasma frequencies of the semiconductor and metal respectively, and ε_I, ε_∞ are frequency independent constants.

The complex propagation constant, β, of the plasmon mode satisfies the well-known dispersion relation (6)

$$\left(\frac{\varepsilon_I}{\gamma_I} + \frac{\varepsilon_s}{\gamma_s}\right)\left(\frac{\varepsilon_I}{\gamma_I} + \frac{\varepsilon_M}{\gamma_M}\right)e^{\gamma_I x_0} = \left(\frac{\varepsilon_I}{\gamma_I} - \frac{\varepsilon_s}{\gamma_s}\right)\left(\frac{\varepsilon_I}{\gamma_I} - \frac{\varepsilon_M}{\gamma_M}\right)e^{-\gamma_I x_0} \tag{10}$$

where ε_s, ε_m, and ε_I are the dielectric constants in the respective regions shown in Fig. (1).

β and R are being calculated for In-Ga_2O_3GaAs - tunnel junctions with the following parameters used: a hole density of $p = 5.0 \times 10^{20}$ cm^{-3}, $\omega_m = 1.92 \times 10^{16}$ rad./sec., $\zeta_m = 2.61 \times 10^{-15}$ sec. [7], $\omega_s = 5.64 \times 10^{14}$ rad./sec., $\zeta_s = 1.0 \times 10^{-14}$ sec., $\varepsilon_\infty = 11.1$ [8], $\varepsilon_b = 3.2$ [9], $E_{FM} = 8.6$eV, $V_a(V=0) = 1.0$eV [10], $E_c - E_v = 1.30$eV [11], $E_v - E_{FS} = .6$eV. The d.c. voltage V_0 is assumed between .65 and .75 volts. Since 11Å anodic oxides have been reported [12], the value of x_0 used was 10Å.

The numerically calculated dispersion in β^1 and β^{11} for the modes supported by this structure are shown in Fig. (2). Especially interesting is the frequency region up to the semiconductor plasma oscillation frequency ω_s. As is shown in Fig. (2), β^1 increases monotonically until ω exceeds $\omega_s/\sqrt{2}$, whereupon β^1 rapidly drops to zero, indicating that the mode cuts off. A second branch appears at higher frequencies. It is not known at the present time whether the gap in the dispersion relation near ω_s is actually present. Gain is expected well below $\omega_s/\sqrt{2}$ for which good confinement is obtained and loss is relatively low. This calculation of the dispersion extends those of Ref. (6) in that the loss is included and hence the regions of anomalous dispersion.

The detailed numerical integration of Eq. (3) utilizing Eqs. (4) through (8) is in the process of being carried out. The S-functions in Eq. (3) allow a trivial integration of three of the six variables of integration. A further can be integrated by invoking the cylindrical symmetry of the problem. This leaves two variables of integration for the numerical procedure, the initial and final momenta directed across the junction. We are attempting to obtain a closed form expression for one of these integrals which would leave a single integral over the initial momentum component directed across the junction. Thus far we have found our numerical calculations to diverge as $\omega \to 0$. According to Eq. (1), and Tucker's analysis, the transition rate R multiplied by ω^2 should be proportional to $\frac{dI}{dV}$. This work is presently continuing.

Conclusions and Outlook:

Our calculations up to the moment indicate that surface electromagnetic wave amplification might prove to be a possibility up through submillimeter wavelengths. The calculation using Eq. (1) indicates that a gain of approximately .4 μm^{-1} is possible in the low frequency limit provided the slowing factor of 200 can be achieved. For this estimate we have used ε_0 in the denominator which can be questioned. On the other hand the dielectric constant of such thin films is also uncertain.

The confinement of the mode (power) to the thin tunneling film is important and will be calculated by using our dispersion relationship calculation, once the numerical gain calculation is obtained.

Experimentally Eq. (2) indicates that the spontaneous emission expected is of the order of 10^{-7} watts which will be difficult to observe using direct detection with presently available detectors. We have made some initial attempts to observe this radiation with point contact tungsten on SnTe junctions. Although an indication of negative resistance was obtained, no spontaneous radiation was detected. Our plans are to pursue this after better numerical estimates are available.

The above calculations are an initial step in attempting to investigate surface electromagnetic wave amplification as a possibility at submillimeter wavelengths. There are several other factors which are expected to be important. More detailed investigations of the fabrication are important. The above calculations of the gain and the matrix element are being done assuming transverse momentum conservation and parabolic bands. The heavy doping of the semicondutor should relax such strict momentum conservation and bandtailing should also be considered. The value of ζ_s, for the semiconductor is believed to be conservative so that the surface plasmon loss could be less lossy than indicated. Degradation of the gain due to surface states, impurity scattering, and dielectric losses in the barrier must also be expected. The fabrication problems associated with 10Å barriers could also be considerable; however molecular beam epitaxy is a possibility.

Associated problems also need addressing, namely the coupling of radiation into and out of the tunneling region. There is a matching problem since the junction mode travels much more slowly than the free space field. The fundamental characteristics of tunneling phenomena at high frequencies also need addressing.

Aside from GaAs, other p^{++} materials such as heavily doped Si and SnTe are possible. SnTe is very interesting, as it has a high hole concentration, small effective mass, and evaporated films retain the semiconducting property.

While it is premature to conclude that surface wave amplification is possible by the utilization of tunneling as a pumping mechanism, the numbers indicate that further effort in this area would be worthwhile.

<u>References</u>

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Figure Captions

Fig. (1). The band structure for the metal-barrier-semiconductor junction structures proposed for surface electromagnetic wave amplification.

Fig. (2). Calculated dispersion relation for TM surface electromagnetic waves propagating in the ideal junction having the band structure of Fig. (1). Parameters are specified in the text. $Re(\beta = \beta^{1})$ and $Im(\beta = \beta^{11})$.

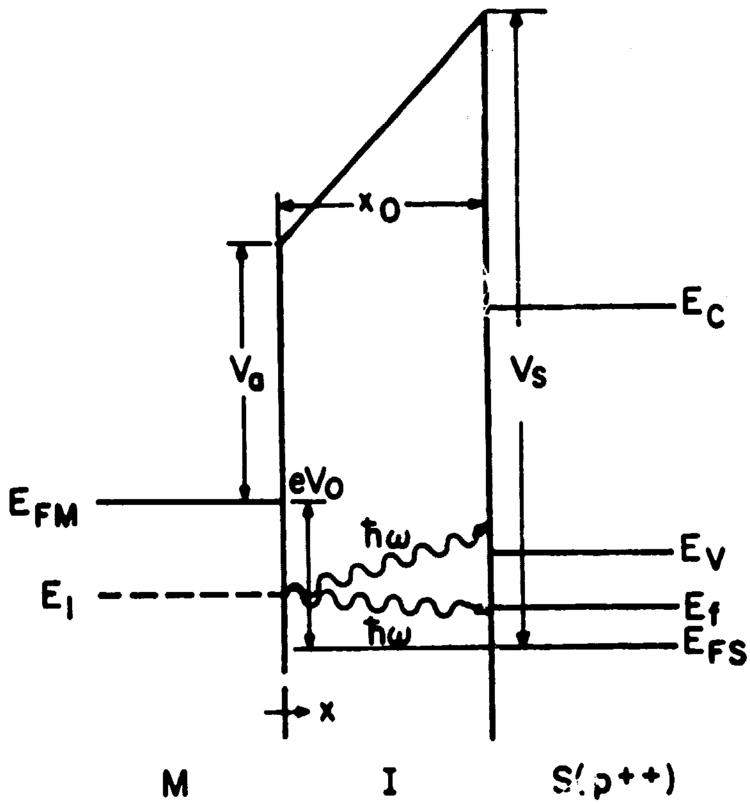
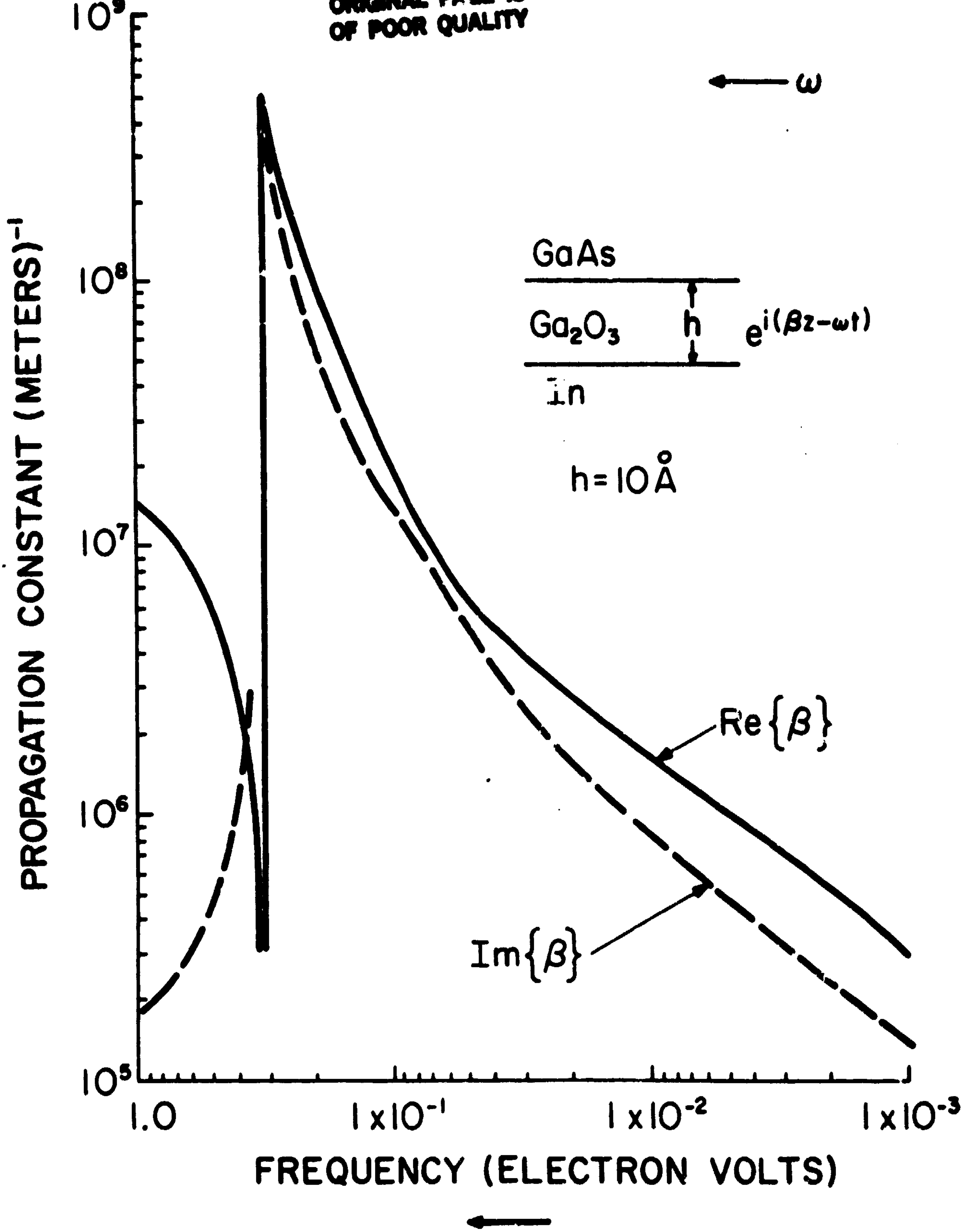


Fig. (1)



ω
GaAs
Ga_2O_3
h
$e^{i(\beta z-\omega t)}$
In
h = 10 Å
Re{β}
Im{β}
10^9
10^8
10^7
10^6
10^5
PROPAGATION CONSTANT (METERS)$^{-1}$
1.0
1×10^{-1}
1×10^{-2}
1×10^{-3}
FREQUENCY (ELECTRON VOLTS)

Fig. (2)