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Letters

Proposal for an Electrically Tunable Surface Plasmon Light Emitter

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***Abstract*—A new scheme is proposed to generate infrared waves by exciting thin-slab plasmon waves by hot-electron injection via a tunneling thin insulator. These plasmon waves are coupled out by a periodic structure, and, by way of example, this is demonstrated for a Karp structure. The calculated numerical values of the example at a wavelength of 15 μm, show that standard semiconductor technology can be used to fabricate the device.**

A Proposed Infrared Emitter Excited by Surface Plasmons

It has been demonstrated experimentally that planar Metal–Insulator–Metal (MIM) junctions can be used to excite radiative surface plasmon modes [1]. There is convincing evidence that enhancement of light emission takes place [2] from such structures (e.g., Al–Al_2O_3–Ag or Mg–MgO–Ag MIM junctions), when the metal surfaces are roughened. While in early experiments, the light emission was very faint, in a more recent experiment [3] which might also partly be based on radiative plasmon modes, it was visible to the naked eye in a darkened room. In this case the substrate was gallium arsenide and the insulating layer was a native oxide. It has to be stated, however, that the exact origin of the GaAs MOS emission has not yet been established and that several other light-emission effects could here simultaneously be responsible for the observed spectrum.

Better control over radiation based on radiative plasmon modes should be achievable by using slow-wave structures instead of random irregularities in the surfaces. This case represents an interesting analogy with space charge waves of an electron beam coupled to a slow-wave structure. Efficient energy transfer would be facilitated when the frequency and the phase velocity for the electromagnetic field and the space charge waves nearly match with each other.

The purpose of this communication is to present a proposal for such an infrared emitter, with possibly even some tunability.

Various combinations are possible for exciting surface plasmons. Here we propose to use hot carriers to be injected by tunneling through a suitably thin insulating layer into a metal or semiconductor layer, where both normal and tangential modes of

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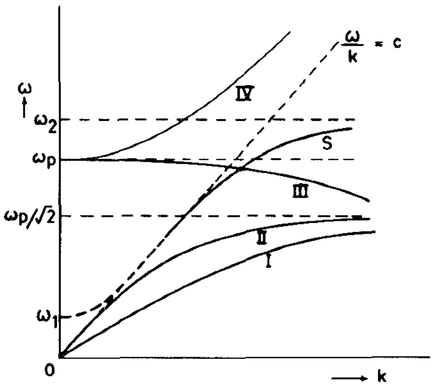

Fig. 1. Dispersion curves for plasma modes and slow-wave structure. ω_1 and ω_2 represent the lower and upper cutoff points for the passband.

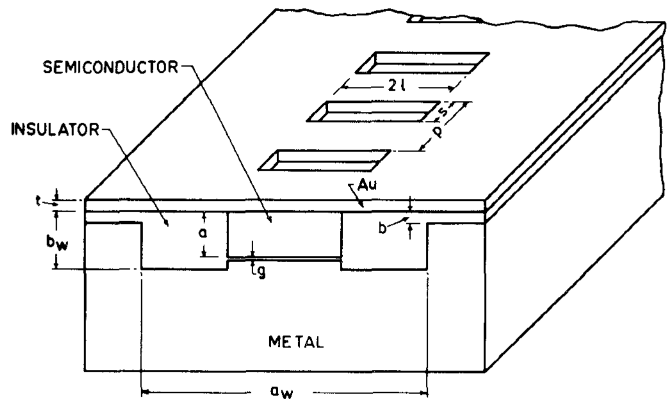

Fig. 2. Plasmon excited infrared emitter—tentative values of parameters for an emitter of $\lambda = 15$ μm, ($a_W = 50$ μm, $b_W = 10$ μm, $a = 8$ μm, $g = 40$Å, $2l = 20$ μm, $p = 12$ μm, $s = 5$ μm, $t = 2$ μm, $b = 2$ μm).

plasmon waves can thus be excited. The characteristics of surface plasmon waves in thin slabs have been studied extensively [4]–[6]. These modes are nonradiative for $\omega/k < C$ (=velocity of light) unless a slow-wave structure couples to it. Such coupling has been verified in the case of emission of radiation by energetic electron beams impinging on a thin metal film [7].

A structure which is similar to the one we propose to employ here, but without the slow-wave structure as a top layer, has been investigated by Economou [6, fig. 6]. As a first approximation to a design approach for choosing the dimensions of a test device, its dispersion characteristics have been adapted for our application and are given in Fig. 1 by curves I, II, III, and IV.

We propose here to use as slow-wave structure the relatively simple and for millimeter waves well-proven Karp structure [8], which is also very suitable for modern semiconductor photolithography. The resulting device is shown in Fig. 2. The dispersion characteristics of the Karp structure used there are given as curve S in Fig. 1. Here ω_1 and ω_2 refer to the cutoff frequency for the ridge waveguide and the maximum frequency, due to slot periodicity, respectively. This dispersion curve for the Karp structure intersects the curve III slightly below the $\omega = \omega_p$ line (ω_p = plasma resonance frequency), where synchronous interaction between plasmon wave and periodic metal structure will take place. The advantage of such a wave interaction is that plasmon waves travel with higher phase velocities than the often unsuccessfully tried case of drifting electron plasmas. Therefore, the wave coefficients can be smaller and thus coupling with the slow-wave structure is stronger since the plasmon waves do not decay very rapidly near the surface. Tentative values for an infrared radiation at a wavelength 15 μm were computed for the structure of Fig. 2. The structure is now described as follows.

The ridge waveguide has two sidewall dimensions a_W and b_W. The semiconductor bar has a thickness a with a thin tunnelling insulator of thickness g, and a width of $2l$ which is the same width as the periodic slots on its opposite surface. The slot periodicity is p, and their width s. The slot-metal film needs to be of a thickness t for sufficient strength and satisfactory coupling. The side walls of the ridged wave guide are produced with an electrical dc isolation from the slotted Au film by a suitable insulator film of thickness b to provide an RF bypass for the infrared signal through the resulting capacitance. In this way the required bias voltage can be applied to the thin film of thickness g to ensure hot-electron injection into the semiconductor. This bias voltage provides the energy for infrared wave generation. It is applied between the gold overlay film and the substrate metal. The injected electrons have to have an energy higher than the plasmon energy. There are several possible ways to produce this structure by photolithographic techniques. Extensions side and length wise are possible for increased power levels.

Applying a bias voltage between the slotted Au film and the semiconductor bar can modify the Schottky-diode space charge layer between Au film and the semiconductor, thus modifying both the coupling and the average plasmon wavelength. The latter parameter determines the frequency of operation which can thus be modulated.

The frequency of wave generation is slightly below the plasma frequency of the semiconductor which we selected for our example to be that of $n = 10^{17}$ cm^{-3}. In view of good Schottky-space charge modulation perhaps GaAs might be advisable.

Thin-film plasmons can be excited of course also along a metal so that the semiconductor can be replaced by a metal film whose carrier density would however be substantially higher. Therefore, the corresponding metal film thickness would have to be correspondingly smaller with the ridge of the waveguide higher.

The details of the dimensions and other properties can of course be modified. Experimental verification will be attempted in the future, where particularly the stability of the tunnelling film needs to receive special attention. Also coupling of fast-mode waveguides with fast plasmon waves such as curve IV in Fig. 1, should be considered.

In conclusion, an infrared emitter is proposed where dimensions have been determined by way of example for a signal of a wavelength of 15 μm. There is of course no reason why this cannot be extended also into the optical range with a suitable submicron technology which has recently become available. The basic new advantage of the scheme advanced here is that the plasmon wave phase velocity can be very high so that coupling to a slow-wave structure is stronger than with the previously attempted drifting semiconductor plasma. The proposed structure can easily be manufactured by standard semiconductor photolithographical technology.

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Correction to "Cylindrical Dielectric Resonators and their Applications in TEM Line Microwave Circuits"

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In the above paper[1] the following correction should be made. Equation (3) should read as

$$F_0^2=(u^2+w^2)\frac{\epsilon_r}{\epsilon_r-1}. \tag{3}$$

This is merely a typographical error and does not affect the other equations or results of the analysis.

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Addendum to "Design of Microwave GaAs MESFET's for Broad-Band Low-Noise Amplifiers"

HATSUAKI FUKUI

It has been called to the author's attention that (3) in the above paper[1] appears to be inadequate [1], especially for scaling [2]. Considering this situation the expression should read

$$R_n=\frac{k_2}{g_m} \tag{3}$$

where $k_2=0.8$.

This modification leads to rewriting (12) as follows:

$$R_n=\frac{40}{Z}\left[\frac{aL}{N}\right]^{1/3}\Omega. \tag{12}$$

Consequently, the numerical values for R_n in Fig. 8 should be, in descending order, 46, 39, 33, 29, 25, 21, 18, and 15. Figs. 9 and 10 are also slightly affected by the revised expression. However, the principal statement and conclusions remain unchanged.

The author wishes to thank Dr. R. A. Pucel for his encouragement concerning this amendment.

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Erratum to "Approximate Formulas for Line Capacitance and Characteristic Impedance of Microstrip Line"

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In the above paper [1], the approximate formula (42) for the characteristic impedance Z of a microstrip line, with substrate dielectric constant ϵ_r and thickness to width ratio h/W, should be

$$Z\simeq\frac{377}{\sqrt{\epsilon_r}}\frac{h}{W}\left\{1-\frac{2}{\pi\epsilon_r}\left(\frac{h}{W}\right)\left[(1+\epsilon_r)\ln\left(\frac{2h}{W}\right)-2.230-4.554\epsilon_r-(4.464+3.89\epsilon_r)\frac{h}{W}\right]\right\}^{-1/2}, \quad \text{for } h/W \text{ small.}$$

The approximate formula (44) for the line capacitance should be

$$\tilde{C}\approx\frac{\pi(1+\epsilon_r)h}{\epsilon_r W}\left\{\ln\left(\frac{8h}{W}\right)+\frac{1}{16(1+\epsilon_r)}\frac{W^2}{h^2}+\frac{\epsilon_r-1}{\epsilon_r}\left[0.041(W/h)^2-0.454\right]\right\}^{-1}, \quad \text{for } h/W \text{ large.}$$

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