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UNCONDITIONALLY STABLE MICROWAVE Si - IMPATT AMPLIFIERS

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ABSTRACT

The purpose of this investigation has been the development of an improved understanding of the design and analysis of microwave reflection amplifiers employing the negative resistance property of the IMPATT devices. Unconditionally stable amplifier circuit using a Silicon IMPATT diode is designed. The problems associated with the design procedures and the stability criterion are discussed. A computer program is developed to perform the computations.

The stable characteristics of a reflection-type Si-IMPATT amplifier, such as gain, frequency and bandwidth are examined. It was found that at large signal drive levels, 7 dB gain with bandwidth of 800 MHz at 22,5 mA was obtained.

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Introduction

The IMPATT diode is considered to be one of the most important two-terminal active solid-state devices which have been developed for generating power at microwave frequencies. The avalanche oscillator was first proposed by Read [1] in 1958 as an n^+pip^+ junction structure.

The basic equations which govern the operation of an IMPATT diode are Poisson's equation and the contiuity equations for holes and electrons. In one dimension they are:

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon}\left(N_D - N_A + p - n \right) , \qquad \text{.....(1)}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G \qquad \text{.....(2)}$$

and

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G \qquad \text{.....(3)}$$

where

$$J_p = q\left[- D_p \frac{\partial p}{\partial x} + p\,\mu_p E\right] , \qquad \text{.....(4)}$$

$$J_n = q\left[D_n \frac{\partial n}{\partial x} + n\,\mu_n E\right] , \qquad \text{.....(5)}$$

$$G = g_d + g + \gamma , \qquad \text{.....(6)}$$

$$g_d = \frac{pn - n_i^2}{\tau_{po}(n + n_1) + \tau_{no}(p + p_1)} \qquad \text{.....(7)}$$

$$g = \frac{1}{q}\left(\alpha_n |J_n| + \alpha_p |J_p| \right) , \qquad \text{.....(8)}$$

$$\alpha_n = A_n \exp\left[-\left(\frac{b_n}{E}\right)^m\right] , \qquad \text{.....(9)}$$

$$\alpha_p = A_p \exp\left[-\left(\frac{b_p}{E}\right)^m\right] , \qquad \text{.....(10)}$$

$$\mu_{n,p} = \mu_{n,p}(E) , \qquad \text{.....(11)}$$

$$D_{n,p} = D_{n,p}(E) , \qquad \text{.....(12)}$$

E = the electric field (V/cm),
q = the electronic charge (C),
$\mathcal{E}$ = the dielectric constant (F/cm),
N_D, N_A = the donor and acceptor densities (cm^{-3}) ,
p, n = the hole and electron densities (cm^{-3}) ,
J_p, J_n = the hole and electron current densities (A/cm^2) ,
g_d = the hole and electron generation-recombination rates ($cm^{-3}\ s^{-1}$) ,
g = the electron-hole pair generation rate due to impact ionization($cm^{-3}\ s^{-1}$) ,
γ = the stochastic electron-hole pair generation rate due to impact ionization or thermal and/or optical generation ($cm^{-3}\ s^{-1}$) ,
α_p, α_n = the hole and electron ionization rates (cm^{-1}),
μ_p, μ_n = the hole and electron mobilities ($cm^2/V\text{-}s$),
p_1, n_1 = the hole and electron concentrations in the conduction band when the single-level trap and the Fermi level are equal ,
A_p, b_p, m=the hole ionization rate constants,
A_n, b_n, m=the electron ionization rate constants and
D_p, D_n = the hole and electron diffusion coefficients.

A lot of reseach work had been done since Read [1] reported his first article [2-7] . Instabilities in the IMPATT diode amplifiers have recently reported by Seddik [8] .

In this investigation, the design of unconditionally stable microwave Si-IMPATT reflection-type amplifiers is discussed. The criterion for stability in the design was taken into account . The diode operation was performed under large signal drive level in the proposed stable design.

Design of Unconditionally Stable Circuits

The design of an unconditionally stable circuit amounts to finding a two-port matching network between the diode and the load (50-Ω resistance) . The network is made up of series and/or parallel coupled TEM lines . The circuit parameters are adjusted so that the circuit gives a proper gain at the desired frequency and at the same time the circuit satisfies the stability criterion 8,

$$D \cong 1 - M_1 M_{-1}\ S_o(S^*_{-1} + S_1)$$
$$= 1 - |M_1|^2\ S_o(S^*_{-1} + S_1) \neq 0$$

since $M_{-1} = M^*_1$ and the value of $|M_1|$ cannot be greater than one.

A computer program was developed to perform these computations . It should be noted that the circuit impedance should be considered in the frequency range from 0 to 1.5 ω_p instead of the frequency above ω_a , the avalanche resonant frequency of the diode . (When searching for a circuit with a desired gain performance, the package equivalent reactance is included in the diode impedance for the sake of convenience. When checking the stability condition, the package reactance is included in the circuit impedance as originally described by Hines[2]). It has been suggested by Hines [2]that a good choice of the circuit should have an impedance with a low resistance and an inductive reactance at the subharmonic frequency . To realize such a circuit, the simplest choice is a $\lambda/2$ long TEM line at a frequency slightly higher than the signal frequency with a low characteristic impedance .

At the subharmonic, the line is approximately $\lambda/4$ long and the resistance is equal to $R_x = Z_o^2/R_L$,where Z_o is the characteristic impedance of the line. Since $Z_o < Z_L$, $R_x < Z_o < Z_L$. At the $\lambda/2$ frequency ,the circuit shows a parallel resonance[9] and $R_x = R_L$. For most diodes $|R_d|$ is less than $R_L (50\Omega)$, ω_p can be chosen between f_0 and $f_0/2$, where the circuit is inductive and R_x is between Z_0^2/R_L and R_L, and therefore the gain can be improved.

Fig. 1 is an example of the matched network. In this figure the circuit impedance, diode impedance, gain, S and S-product are plotted as functions of frequency. The maximum gain is 15.4 dB at 8 GHz and the 3-dB bandwidth is 350 MHz. The gain can be improved by further reduction of Z_0 and a slight increase of the line length .

The S-parameter is never less than one in the passband frequency of the amplifier. Fortunately, the product is not purely real and the product decreases to less than one in most frequencies . It is real and less than one at $(\frac{1}{2})\omega_p$. Therefore the circuit is unconditionally stable.

Another possible choice is a $\lambda/4$ transformer in parallel with a $\lambda/2$ line which has an open end . The transformer will lower the circuit resistance at the pump frequency for a suitable gain while the open shunt reduces the circuit resistance at the subharmonic of the pump frequency. Fig. 2 is an example. The circuit resistance near the pump frequency is nearly constant and $dX_x/d\omega<0$. Such a circuit reactance gives the amplifier wider bandwidth[9] because $dX_d/d\omega>0$. The calculated gain is 18.6 dB and the 3-dB bandwidthis 500 MHz . The S-product indicates that the circuit is unconditionally stable.

Increasing the characteristic impedance of the $\lambda/4$ transformer from 25 Ω to 28 Ω reduces the amplifier gain to 13.4 dB and increases the 3-dB bandwidth to 1 GHz. It is noted that the gain calculated here are small-signal gain. When the input power is higher, the gain should be smaller and the bandwidth wider .

Comparing these two types of circuit shows that the latter is superior to the former. But the simple configuration of the former circuit permits easy construction in a coaxial circuit. The latter is suitable for microstrip fabrication.

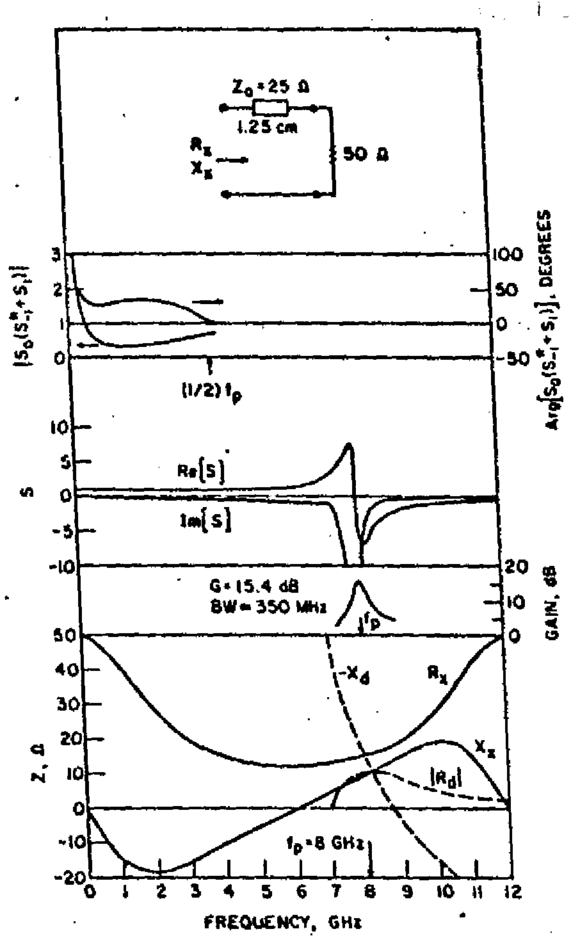

FIG.1 A MATCHING NETWORK AND THE CALCULATED DIODE PERFORMANCE. (R_x, X_x WITHOUT PACKAGE AND R_d, X_d WITH PACKAGE)

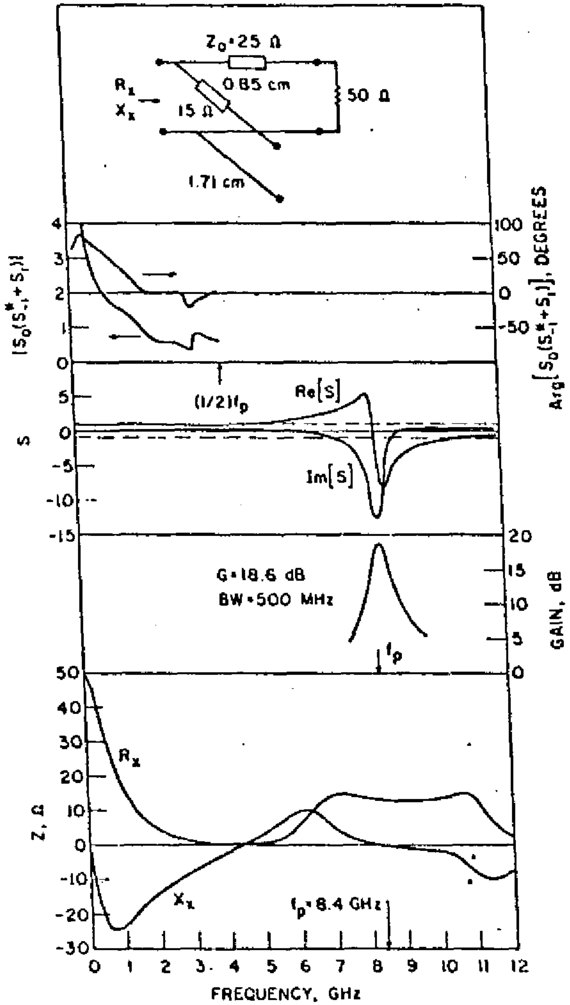

FIG. 2 A MATCHING NETWORK AND THE CALCULATED DIODE PERFORMANCE.

Conclusions

Due to the nonlinearity of the avalanche process in the IMPATT devices under large RF drive levels, the parametric instabilities are originated. It can be eliminated with a properly designed circuit which satisfies the unconditional stability criterion . Two types of TEM line circuits are found to be acceptable . The first one is the $\lambda/2$ line with Z_0 smaller than the load resistance . The second one is a $\lambda/4$ transformer in shunt with an open-end $\lambda/2$ TEM line.

Both types of circuit reduce the circuit resistance at the subharmonic frequency. The first one can easily be built in a coaxial circuit; the second one is more suitable in the microstrip circuit .

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