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Generation and Amplification of Microwave Power in Submicron n^+nn^+ Diodes

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Abstract

The current voltage characteristics and the spectra of the: small-signal response, current self-oscillations, and microwave power generation are analyzed by means of a theoretical simulation of near micron InP diodes. To this purpose, both the hydrodynamic and Monte Carlo approaches are used and compared. Good agreement with available experimental data is obtained.

1. Introduction

Wide-band generation of microwave power in the frequency range $100 < f < 200\ GHz$ has been recently observed experimentally in near-micron n^+nn^+ InP diodes [1,2]. Because of the short active-length involved, non-local effects such as velocity overshoot become dominant and the mechanism of generation is associated with the transit of an accumulation layer across the diode rather than the propagation of a dipole domain. The aim of this work is to present a theoretical analysis of the transport characteristics which are exhibited by the diode under a stable generation of microwave power.

2. Theory and results

The diode characteristics are simulated on the basis of both a kinetic and hydrodynamic (HD) approach. The model warrants a one-dimensional geometry, therefore macroscopic quantities normalized to unit cross-sectional area are considered in the following. The kinetic approach makes use of a numerical solution of the Boltzmann equation through an ensemble Monte Carlo (MC) method which is coupled self-consistently with a Poisson solver. We take a nonparabolic conduction band structure with Γ-L-X valley ordering, and account for impurity, acoustic and polar optical phonon scattering in each valley as well as intervalley scattering between each couple of equivalent and non-equivalent valleys with spherical equienergetic surfaces. The HD approach makes use of the set of conservation equations for number, velocity and energy in the single-electron gas model and it is coupled with a

Poisson solver [3]. Input parameters of this approach are the energy dependence of the average moments (up to the third) and scattering rates of the bulk material as provided by MC calculations under stationary and homogeneous conditions. Abrupt homojunctions are assumed and the parameters of the InP diode are taken close to those of the experiments [1,2] as: $n^+ = 10^{18}\ cm^{-3}$, $n = 2 \times 10^{16}\ cm^{-3}$, the cathode, n-region and anode lengths respectively of 0.1, 1.0 and 0.3 μm. Since a simulation of the same physical situation with the HD approach has the advantage of requiring a considerably simpler and faster computer enviroment when compared with the kinetic approach, we use the former to perform all calculations and the latter only for validation purposes.

Calculations performed at room temperature are summarized in Figs. 1 to 5. Figure 1 reports the current-voltage characteristics of the unloaded diode as calculated by the HD (lines) and kinetic (full circles) approaches for a constant voltage U_d applied to a diode. Both approaches predict the onset of a nonvanishing self-oscillation of the current I in the narrow region of values $2 \leq U_d \leq 5\ V$. As an example, the insert in Fig. 1 shows the time dependence of the current in the presence of self-oscillations as calculated by the kinetic approach for $U_d = 3\ V$. The current self-oscillations are caused by a periodic transit across the diode of an accumulation layer which is formed near the center of the n-region due to the joint action of velocity overshoot and Gunn effects. The amplitude of the self-oscillations obtained by the HD approach is shown by the dashed lines. In the region $2V \leq U_d \leq 5\ V$ the solid line and the circles show the mean values of I averaged over the period of the self-oscillations. For diodes with the same length of the n-region, the starting of the self-oscillations in the low-voltage region is found to be almost independent of n. On the contrary, the ending in the high-voltage region is found to depend on n as follows. By increasing n it shifts to higher voltages and by decreasing n it shifts to lower voltages until the region of self-oscillations disappears for $n \leq 1 \times 10^{16}\ cm^{-3}$. The appearance of current self-oscillations evidences that the diode can be used for microwave generation. Therefore, to obtain detailed information we have calculated the frequency dependence of the small-signal admittance and impedance, $Y_d(f)$ and $Z_d(f)$, respectively. For this purpose, we use a small signal analysis previously developed [3]. In the general case, a negative sign of the real part of $Z_d(f)$, $Re[Z_d(f)]$, represents the necessary condition for a small-signal amplification at the given frequency. In the case of interest this condition is fulfilled in a rather wide region of f and U_d. (As an example, Fig. 2 shows the negative part of $Re[Z_d]$ (continuous line) calculated for $U_d = 3\ V$.) The frequency regions corresponding to negative values of $Re[Z_d]$ are plotted in Fig. 3 as a function of the applied voltages. These regions, whose boundaries are shown by the continuous lines, define the amplification bands in the (f, U_d)-plane. In each band the dashed line corresponds to the frequency at which $Re[Z_d]$ is minimum. It should be remarked that at the highest voltages an additional amplification band is found. The frequency region where $Re[Z_d]$ is negative ranges from 90 up to 240 GHz for $4.5 \leq U_d \leq 6\ V$, and agrees well with the experimental values for microwave generation [1,2]. This region is much wider than that corresponding to self-oscillations, as can be seen by the full circles in Fig. 3 which refer to the $f - U_d$ region where self-oscillations are present. The imaginary part of Z_d, $Im[Z_d]$, determines the resonance condition which, for the series resonant circuit consisting of the external inductance L and the load resistance R, takes the form $L = -Im[Z_d]/(2\pi f)$. A positive value of L corresponds to the inductance of the external circuit. The frequency region of positive L for $U_d = 5\ V$ is presented in Fig. 4 by the dot-dashed curve. However, in the region of self-oscillations, L is negative. This indicates that the diode can generate without an external circuit. The frequency region of negative L is presented in Fig. 2 by the dotted curve. Here, L is found to become negative only around the maximum frequency for amplification which, in turn, corresponds to the shortest transit-time of the accumulation layer. This is the frequency region of the self-oscillations which is presented in Fig. 3 by full circles. Thus, the linear analysis provides an estimate for the values of the parameters of the external resonant circuit which are needed for generation. For instance, we find that R must be less than $1\times10^{-8}\ \Omega m^2$ (which from Fig. 2 is the maximum value of $|Re[Z_d]|$) and L must be less than $4\times10^{-20}\ Hm^2$ (see Fig. 4). By using these estimates, within the HD approach we have simulated the diode performances in the series resonant circuit for three sets of values of the total voltage applied to the circuit U and R, namely: (i) $U = 5.5\ V$, $R = 5\times10^{-10}\ \Omega m^2$; (ii) $U = 7.5\ V$, $R = 2.5\times10^{-9}\ \Omega m^2$; (iii) $U = 10\ V$, $R = 5\times10^{-9}\ \Omega m^2$. In all cases, U_d is found to be of about 5 V. The frequency variation in each set is obtained by changing L from 10^{-22} to $3\times10^{-20}\ Hm^2$. Such a variation of the generation frequency is very similar to that obtained experimentally by changing only one parameter, that is the length of the resonance cavity in which the diode is placed [1,2]. For the sake of providing a comparison with the linear theory, these results are summarized in Fig. 4. Here the largest difference is obtained for small values of the resistance, when the deviations from the linear theory are most pronounced (i.e. the current oscillations exhibit an amplitude greater than the average value). Nevertheless, the predictions coming from the linear theory serve as good estimates of the inductance necessary for generation. The efficiency of the generation is finally presented in Fig. 5 where full circles refer to a comparative kinetic calculation. The good agreement we have found between the results of the HD and the kinetic approach strongly supports the physical reliability of our modeling.

3. Conclusions

We have presented a theoretical analysis of linear and nonlinear response characteristics of microwave generators made with near-micron n^+nn^+ InP diodes. The comparison between a kinetic and a hydrodynamic approach supports the reliability of the second approach which has the advantage of requiring a simpler and faster computer enviroment. The frequency range for generation and the estimated efficiency are found to agree well with experiments [1,2]. We would emphasize that by extending the above analysis to the case of submicron GaAs and InP diodes we have found a maximum increase of the generation frequency up to values in the range $600 - 800\ GHz$ when the length of the n-region is reduced to sizes within $0.3 - 0.2\ \mu m$.

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References

[1] A. Rydberg, Int. J. IR and MM Waves, **11**, 383 (1990).

[2] A. Rydberg, IEEE Electron. Dev. Lett., **11**, 439 (1990).

[3] V. Gružinskis, E. Starikov, P. Shiktorov, L. Reggiani, M. Saraniti and L. Varani, Appl. Phys. Lett. **61**, 1456 (1992).

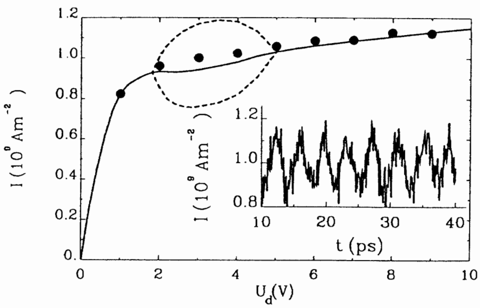

Figure 1: Current-voltage characteristics of the n^+nn^+ InP diode calculated with the HD (lines) and the kinetic (full circles) approaches. Dashed lines show the amplitude of self-oscillations. The insert shows the current self-oscillations within the kinetic approach for $U_d = 3\ V$. Diode parameters are: $n^+ = 10^{18}\ cm^{-3}$, $n = 2 \times 10^{16}\ cm^{-3}$, $l_1^+ = 0.1$, $l_n = 1.0$, $l_2^+ = 0.3\ \mu m$.

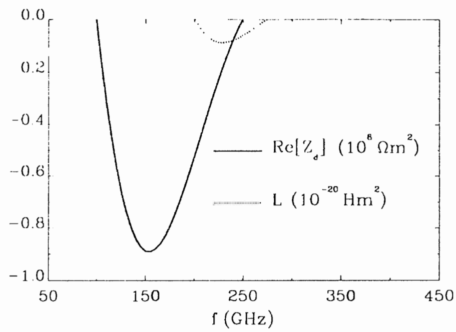

Figure 2: Spectra of the negative parts of $Re[Z_d]$ and L calculated with the HD approach for $U_d = 3\ V$.

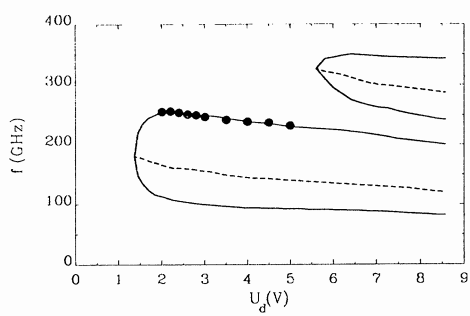

Figure 3: Amplification band diagram. Dashed lines refer to $min\{Re[Z_d]\}$. Points to the self-oscillations region.

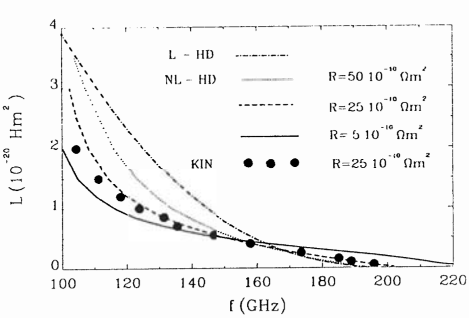

Figure 4: Inductance spectra. L-HD, NL-HD, KIN refer to linear HD, nonlinear HD, and kinetic approaches.

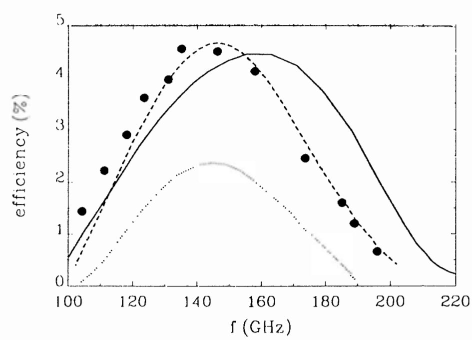

Figure 5: Efficiency of the microwave power generation. The notation is the same of Fig. 4.