MITATT Mode in DDR Heterostructure Impatt

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Abstract. Large signal characterisation of double heterostructure DDR Impatt diode has been carried out in the millimeter-wave range considering the MITATT mode of operation. The structure of the device is p⁺−p₂−p₁−n₁−n₂−n⁺ where impact ionisation and tunneling takes place in the p₁−n₁ region. In this study we have considered two well-known heterostructures, e.g., InP/GaInAs/InP and InP/InGaAsP/InP and one nonconventional structure GaAs/InP/GaAs. The theoretical results of the performances of these devices as regards of output power, efficiency, and negative conductance revealed that the structures are quite promising as the source of power in the millimeter-wave range. The analysis may be used for other mm wave DDR heterostructure Impatts.

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The ever increasing demand of the radar and missile seekers for solid-state power sources in the millimeter-wave frequency range having higher power and efficiency can be met to some extent with the existing devices through the use of heterostructures. It is possible to produce high output power and efficiency by suitably combining different semiconductors to form heterojunctions. In order to improve the efficiency Kuvas et al. [1] proposed a heterojunction Impatt structure which combines a low-band-gap semiconductor for the avalanche zone with a large-band-gap material for the drift region. The fabrication and successful operation of Ge/GaAs heterostructure Impatt has been reported by Namordi et al. [2] where it was shown that the new heterostructure could give a conversion efficiency higher than that of GaAs read diode. The characteristics of Ge/GaAs has also been studied extensively [3]. The same combination of heterojunction was also considered by Pal and Khan [4] where a new heterojunction DDR Impatt structure p⁺−p₂−p₁−n₁−n₂−n⁺ was proposed.

Recently studies have been made on the GaInAs/InP heterojunction SDR Impatt diode [5] where it has been shown that the existence of current injection due to generation-recombination phenomenon and tunneling results in a large decrease in available efficiency. From the results presented in [5] it is found that the performance obtained in the X-band with GaInAs/InP structures are close to those of GaAs Hi–Lo and Lo–Hi–Lo Impatt diodes but the influence of tunnel or saturation current becomes less and less as the frequency increases. So the GaInAs/InP heterostructure Impatt diode has been predicted to be very attractive in the mm-wave frequency range using the MITATT mode by combining tunneling and avalanche multiplication. A finite difference large-signal Impatt diode simulation employing the drift diffusion approximation for the particle current has also been carried out by Mains et al. [6]. The simulation included the energy and momentum relaxation effects. The results obtained from the above simulation were then compared with those of experimental values which indicated that energy and momentum relaxation effects become important above 20 GHz. However, in the analytical method inclusion of the effect of energy and momentum relaxation will complicate the analysis and no direct solution is possible. The DDR Impatt is superior in its performance compared to SDR Impatt so far as the efficiency and power output are concerned. In the present paper, we, therefore, have carried out a large-signal analysis of a double-heterojunction DDR Impatt of the structure p⁺−p₂−p₁−n₁−n₂−n⁺ [4] which is capable of working in the millimeter-wave frequency range. The combina-
tions like InP/GaInAs/InP, InP/InGaAsP/InP, and GaAs/InP/GaAs have been chosen which were found to be more attractive regarding their performances at millimeter-wave frequencies. In fact, GaInAs/InP heterojunction can be obtained technologically with a good-quality interface [5] which rendered the above combination suitable for heterostructure avalanche photodiodes, lasers etc. Since in the millimeter-wave range the width of the depletion region is very narrow and the field required for ionisation is high, significant current begins to flow by means of band-to-band tunneling process. In the device under consideration such tunnel current will flow in the avalanche zone ($p_1-n_1$ region) only. In our analysis we have, therefore, considered the MITATT mode of operation. The effect of the finite reverse saturation current and the tunnel current in the $p_1-n_1$ region have been taken into account. In the $p^+\text{ }n_1-n_2-n^+$ SDR structure the carriers tunnel in the $p^+-n_1$ region, which enhances the injection current degrading the efficiency. In the present case the tunneling current is much less compared to that of SDR structure. This flow of tunnel current in the reverse biased $p_1-n_1$ region makes both the dc and ac current increase. It is found that the increase in dc current is larger than the increase in ac current due to tunneling resulting to a slight degradation of efficiency.

The lattice mismatch between the semiconductors forming heterojunction is very small in the present case, so the effect of interface states in the heterojunction can be neglected and the continuity of the electric displacement vectors on the two sides of the heterojunction can be assumed. In fact, the lattice mismatch also will not affect the results very much because under high reverse electric field required for breakdown the regions are totally depleted. Among the three structures considered here the first two are of the conventional type [1] where a low-band-gap semiconductor (ionisation is easy) has been used for the avalanche zone and a large-band-gap material (ionisation is difficult) for the drift zone. The third heterojunction structure though not of the conventional type, can also give high power output and high efficiency. The expressions for the output power, efficiency and admittance of the device under large signal condition have been obtained analytically and their variation with different controllable parameters have been studied. The theory will be presented in the next section.

Theory

The double heterostructure DDR Impatt under consideration is of the $p^+-p_2\text{ }p_1-n_1-n_2-n^+$ structure [4] and is shown in Fig. 1 along with a typical field profile. When the device is reverse biased to avalanche break-down, the $p_1-n_1$ region represents the avalanche zone where impact ionisation takes place and $p_2$ and $n_2$ regions correspond to two drift zones on the two sides of the avalanche zone.

The large-signal conduction-current density in the avalanche zone can be given by [7]

$$J_c = \frac{(1 - M_p)J_{ps} + (1 - M_n)J_{ns}}{\omega \tau_a} \times \sum_{n=-\infty}^{\infty} \left( -1 \right)^n \frac{I_n(B)I_{q+n}(B)e^{i\phi_{ext}}}{A + j(q+n)},$$

(1)

where $J_{ns}$ and $J_{ps}$ are the thermally generated electron and hole current densities, and $M_p$ and $M_n$ are the complex multiplication factors in the avalanche zone for electrons and holes, respectively. $I_n$ and $I_{q+n}$ are the $n$th and $(q+n)$th modified Bessel functions. $A$ and $B$ are the quantities to be evaluated later. $\tau_a$ is the transit time in the avalanche zone.

The boundary conditions used in this evaluation are as follows:

at

$$x = x_{d1}, \quad J_p = M_p J_{ps}, \quad J_n = J_{ns},$$

and

$$x = x_{a}, \quad J_p = J_{ps}, \quad J_n = M_n J_{ns}.$$  \hspace{1cm} (2)

The dc and the fundamental components of currents can be obtained from the above equation by setting $q = 0$ and 1, respectively, in (1). The total current density includes conduction current density and displacement current density. The fundamental component of current density can be written as

$$J_{d1}(1) = J_c(1) + j\omega C_0 V_a,$$

(3)