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Terahertz Oscillations in p-Type Quantum-Well Oscillators

J. C. Cao*, A. Z. Li*

*State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, P. R. China

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Abstract

We have theoretically investigated steady-state carrier transport and current self-oscillation in negative-effective-mass (NEM) p^+pp^+ diodes. The current self-oscillation here is a result of the formation and traveling of electric field domains in the p base having a NEM. The dependence of self-oscillating frequency on the applied dc voltage is obtained by detailed numerical simulations. In the calculations, we have considered the scatterings by carrier-impurity, carrier-acoustic phonon, carrier-polar-phonon, and carrier-nonpolar-phonon-hole interactions. This kind of NEM oscillator allows us to reach a current oscillation with terahertz frequency, thus it may be used as a broadband source of terahertz radiation.

1. Introduction

Nonlinear dynamics of negative-effective-mass (NEM) semiconductors [1-6] has recently been a very active research field, mainly due to the potential applicability of terahertz (THz) oscillators [2,4]. When an p^+pp^+ NEM diode is subject to a dc bias, damped or undamped current self-oscillating mode shows up depending on the applied dc bias. The undamped mode gives rise to periodically oscillating current related to the formation and traveling of high-electric-field domains. In contrast, when an external electromagnetic radiation acts on the dc-biased NEM p^+pp^+ diode, the interesting physics phenomena increase dramatically, including current synchronization, mode locking, and spatio-temporal chaos. Theoretically, these current-voltage characteristics can be simulated as the response of the carriers in the p-base of p^+pp^+ NEM diode to a time-dependent external driving voltage. In this paper, we theoretically investigate current-voltage characteristics of the p^+pp^+ NEM diode driven only by a dc bias. We yield some complex patterns of time-dependent self-oscillating currents, and calculate the dependence of the self-oscillating frequencies on the dc biases.

2. Velocity-Field Relation of Nem Semiconductors

We abstract an analytical NEM model dispersion from the ground subband of a p-type quantum well (QW) [1,7] as follows,

$$\varepsilon(\mathrm{k})=\frac{1}{2}\left[\frac{\hbar^2 \mathrm{k}^2}{2\mathrm{m_e}}-\sqrt{\left(\frac{\hbar^2\mathrm{k}^2}{2\mathrm{M_e}}-\varepsilon_0\right)^2+4\triangle^2}+\sqrt{\varepsilon_0^2+4\triangle^2}\right] \tag{1}$$

in which k = (k_x, k_y, k_z) is the wave-vector, $m_e = Mm/(M+m)$, and $M_e = Mm/(M-m)$ with m and M two effective masses, and $\varDelta$ and ε_0 are two energy-band-related energies. When $M \rightarrow m$, the dispersion (1) reduces to a parabolic band. In the calculations, we set $\varepsilon_0 = 0.1$ eV, $\varDelta = 0.02$ eV, $m = 0.085\, m_0$ (m_0 is the free electron mass), and $M = 0.44\, m_0$, respectively. By the balance-equation theory [8], we have calculated carrier drift velocity v_d as a function of steady-state electric field E in the x-direction at lattice temperature T = 77 K, by accounting for the scatterings from carrier-impurity, carrier-acoustic-phonon (deformation and piezoelectric), carrier-polar-optic-phonon, and carrier-nonpolar-optic-phonon. In Fig. 1 we show the calculated carrier drift velocity v_d as a function of steady-state field E at lattice temperature T = 77 K. In the case of the parabolic band (solid circles), drift velocity monotonously increases with increasing electric field. In contrast, the velocity-field curve in the NEM nonparabolic case (solid squares) has a N-shaped negative differential velocity (NDV) with a peak velocity about 2.04×10^7 cm/s at the critical electric field of 6 kV/cm. After about E > 22 kV/cm, the differential velocity becomes positive. The solid line in Fig. 1 is an analytical fit to the balance-equation-calculated N-shaped velocity-field relation by the following expression,

$$v_d = 1.36204E\left(1 - \frac{E^2 + 5.46062}{E^2 + 1.34883E + 13.57118} + 0.01738 \arctan(0.42774E - 10.82297)\right) \quad (2)$$

which is fed into the transient drift-diffusion equations and the Poisson equation [5] to calculate current density in the NEM p^+pp^+ diode driven by a dc voltage. The total current density $J(t)$ is defined by the sum of the conduction current density and the displacement current density.

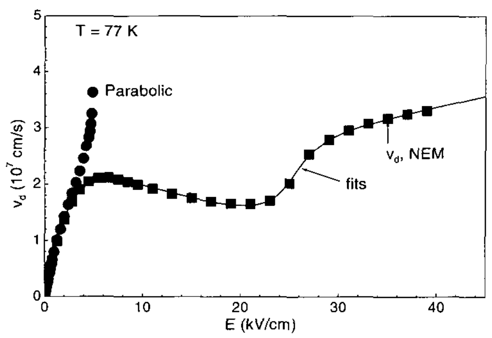

Fig. 1. Calculated carrier drift velocities as a function of electric field.

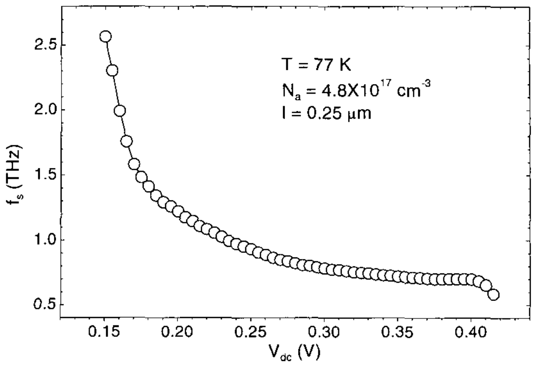

Fig. 2. Self-oscillating frequencies of the dc-biased NEM diode.

3. The Self-Oscillating Current

We consider the p^+pp^+ NEM diode driven by a dc bias. The p-base length is set to be l = 0.25 μm, the doping concentration in the p-base is N_a = 4.8×10^{17} cm^{-3}, and lattice temperature is T = 77 K. To mimic a realistic situation, a slight doping notch is assumed near the cathode end of the p^+pp^+ NEM diode. We solve the spatial and temporal evolution of the electrostatic potential and carrier density, which are self-consistently used to calculate current density. In the NDV region, a small doping inhomogeneity can cause the growth of an carrier accumulation layer and lead to the formation of high-field domain and current oscillation [9-11]. For the p^+pp^+ NEM structure considered here, the dynamic dc voltage band is V_{dc} from 0.15 V to 0.415 V, in which dynamic electric-field domain is formed in the p-base and the self-oscillating current shows up with a frequency f_s. When the dc voltage is beyond the dynamic dc voltage band, only the static electric-field domain is formed, *i.e.*, the current density approaches a constant after the initial transient. In Fig. 2 we show the bias-dependent self-oscillating frequencies f_s, which decrease from 2.6 to 0.6 THz with increasing dc voltages from V_{dc} =0.15 to 0.415 V. Specially, when V_{dc} = 0.18 V the self-oscillating frequency f_s = 1.413 THz.

4. Conclusions

In conclusion, we have theoretically investigated current self-oscillation of dc-biased NEM p^+pp^+ diodes. The self-oscillating currents are the results of the formation and traveling of electric-field domains in the *p*-base having a NEM. The self-oscillating frequency lies in the THz range for the NEM p^+pp^+ diodes having submicrometer *p*-base lengths. It is suggested that the NEM p^+pp^+ diode may be used as an electrically tunable THz-frequency source. Also, the present discussions on nonlinear dynamics of NEM semiconductors would be very useful for studying quantum-well-based opto-electronic devices [12-15].

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