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Field-domain dynamics and current self-oscillations in negative-effective-mass terahertz oscillators

J. C. Cao† and M. Qi

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

Abstract

Field-domain dynamics and current self-oscillations are theoretically studied in quantum-well (QW) negative-effective-mass (NEM) $p^{+}pp^{+}$ diodes when the electric field is applied along the direction of the well. The origin of current self-oscillations is the formation and traveling of electric-field domains in the *p*-base. We have accurately considered the scattering contributions from carrier-impurity, carrier-acoustic phonon, and carrier-optic phonon. It's indicated that, both the applied bias and the doping concentration largely influence the current patterns and self-oscillating frequencies, which lie in the THz range for the NEM $p^{+}pp^{+}$ diode with a submicrometer p-base. The complicated field-domain dynamics is presented with the applied bias as the controlling parameter.

Keywords : Field-domain, terahertz, self-oscillation, negative-effective-mass.

1. Introduction

Much effort is recently devoted to the experimental and theoretical studies of the terahertz (THz) generation and THz applications [1-3]. The experiments [4,5] show that the dispersion relation for the ground subband of a *p*-type quantum well (QW) of zink-blende-like semiconductors contains an extensive section with the negative-effective-mass (NEM) due to the spin-orbit coupling of heavy- and light-hole states and the symmetry breaking of the quantum well potential. By abstracting an analytical NEM dispersion relation from a *p*-type QW subband, the calculations of carrier transport in $p^{+}pp^{+}$ diodes with a NEM *p*-base have been performed, by using the collisionless Boltzmann equation [6-8] and the nonparabolic balance equation theory [9]. Calculations [10] indicated that the steady-state velocity-field curve of carriers with a NEM dispersion supports a *N*-shaped negative differential velocity (NDV) section, which can lead to the formation of electric-field domains and self-oscillating currents. The existence of the oscillatory regime and its features mainly depend on the form of the dispersion relation. The frequency may be controlled by changing the QW width and the doping concentration. The self-oscillating frequency lies in the THz range for the NEM $p^{+}pp^{+}$ diodes having submicrometer *p*-base lengths.

In this work, we focus on the calculations of field-domain dynamics and self-oscillating current patterns in the NEM $p^{+}pp^{+}$ diodes with the applied bias as controlling parameters. We accurately include different scattering contributions by impurity, acoustic phonon, and optic phonon. The resulting N-shaped velocity-field relation is then fed into the transient drift-diffusion model and Poisson equation to study spatiotemporal electric-field domain and self-oscillating characteristics of the NEM $p^{+}pp^{+}$ diode. Detail calculations indicate that the carriers having a NEM may give rise to a

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† E-mail : jccao@mail.sim.ac.cn

rich variety of spatiotemporal current patterns and self-oscillating behaviors. Both the applied bias and the doping concentration could influence the patterns and self-oscillating frequencies.

2. Negative differential velocity of nagative-effective-mass semiconductors

We consider a NEM wavevector-energy dispersion abstracted from the ground subband of a *p*-type quantum well [6,10]. According to the nonparabolic balance-equation theory [9,11], we have calculated carrier drift velocity vd as a function of steady-state electric field *E* at lattice temperature T=77 K, by accounting for the scatterings from carrier-impurity, carrier-acoustic-phonon, and carrier-optic-phonon. All material constants used in calculations are typical values of GaAs: lattice density d=5.31 g/cm^3, transverse sound velocity v_{st}=2.48×10^3 m/s, longitudinal sound velocity v_{sl}=5.29×10^3 m/s, LO phonon energy Ω_{LO}=35.4 meV, low-frequency dielectric constant κ =12.9, optical dielectric constant κ_∞=10.8, valence-band deformation potential Ξ= 8.5 eV, and piezoelectric constant e_{14}=1.41(109 V/m. The velocity-field curve for the NEM semiconductor has a *N*-shaped NDV, which is the origin of the formation of electric-field domain and current self-oscillation in the present NEM diodes.

3. Field-domain dynamics and current self-oscillation

The *N*-shaped NDV velocity-field relation is fed into the transient drift-diffusion model and the Poisson equation to study the electric-field domain and self-oscillating characteristics of the dc-biased p^+pp^+ diode with a NEM *p*-base. We solve the spatial and temporal evolution of the electrostatic potential and carrier density as two fundamental variables, which are self-consistently used to calculate all other quantities. The total current density $J(t)$ is the sum of the conduction current density and the displacement current density. In the NDV regime, a small doping inhomogeneity can cause the growth of a carrier accumulation layer and lead to the formation of high-field domain and current oscillation. Throughout the paper, the p-base length of the NEM p^+pp^+ diodes is set to be l=0.1 (m, and the lattice temperature is T =77 K. The doping concentration in the contact p^+-region is assumed to be 2×10^{18} cm^{-3}, and the *p*-region doping concentration is N_a=3×10^{17} cm^{-3}.

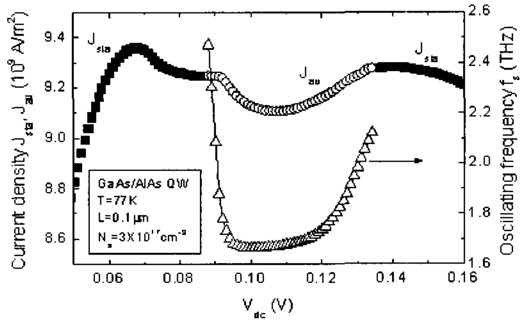

Fig. 1. Dependence of the time-averaged current density J_{av}, static current density J_{sta}, and the self-oscillating frequency f_s (right axis) on the dc biases from 0.05 to 0.16 V.

When a dc bias, V_{dc}, is applied to the NEM p^+pp^+ structure for the given *p*-region doping concentration, N_a, there is a region of dc voltage band, V_{dc} ∈[0.088, 0.134 V], in which dynamic electric-field domain is developed 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 (define as Jsta) after the initial transient dies out. We define the time-averaged current density J_{av} by integrating $J(t)$ over one oscillating period (=1/f_s). In Fig. 1 we show the dependence of time-averaged current density J_{av}, static current density J_{sta}, and self-oscillating frequency f_s (right axis) on dc biases from V_{dc}=0.05 to 0.16 V. The region of V_{dc} ∈ [0.088, 0.134 V] shown by open circles is the dynamic band, in which dynamic electric-field domain is developed and oscillates with a frequency f_s. It changes in the THz range from 0.1 THz to 2.49 THz. To have a clear insight into spatiotemporal evolution of carrier dynamics, In Fig. 2 we have shown electric-field domains in the

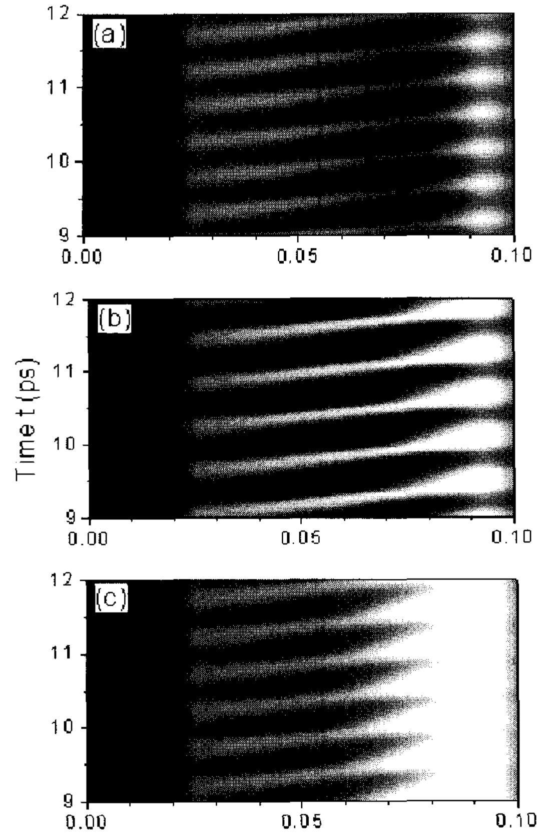

Fig. 2. Spatiotemporal electric-field domains in the NEM diode are shown as the density gray plots, where lighter areas correspond to larger amplitudes of the electric fields. The applied dc biases are: (a) V_{dc}= 0.09 V, (b) 0.1 V, and (c) 0.13 V, respectively.

NEM diode at different biases: (a) V_{dc}=0.09 V, (b) 0.1 V, and (c) 0.13 V, respectively. The spatiotemporal electric-field domains are shown as the density gray plots, where lighter areas correspond to larger amplitudes of the electric fields. It's clearly seen that the electric-field domain periodically travels in the diode with the evolution of time.

4. Conclusions

The dependence of current self-oscillation and its patterns on the applied bias are investigated in the dc biased NEM p^+pp^+ diode. When the p^+pp^+ diode with a NEM p-base is subjected to a dc bias in the negative-differential-velocity region, the dynamic electric field domain is formed, leading to a current self-oscillation with a frequency in the THz range. It's clearly shown that the electric-field domain periodically travels in the diode with the evolution of time. The interesting patterns of self-oscillating currents and field-domain dynamics are shown when changing the dc biases. The NEM-induced current self-oscillation may be used to develop a tunable THz-frequency oscillator.

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References

[1] B. E. Cole, J. B. Williams, B. T. King, M. S. Sherwin, and C. R. Stanley, Nature **410**, 60 (2001).

[2] P. H. Siegel, IEEE Trans. Microwave Theory Tech. **50**, 910 (2002).

[3] B. Ferguson and X. C. Zhang, Nature Materials **1**, 26 (2002).

[4] R. K. Hayden, D. K. Maude, L. Eaves, E. C. Valadares, M. Henini, F. W. Shears, O. H. Hughes, J.C. Portal, and L. Cury, Phys. Rev. Lett. **66**, 1749 (1991).

[5] J. A. Kash, M. Zachau, M. A. Tischler, and U. Ekenberg, Semicond. Sci. Technol. **9**, 681 (1994).

[6] Z. S. Gribnikov, A. N. Korshak, and N. Z. Vagidov, J. Appl. Phys. **80**, 5799 (1996).

[7] A. N. Korshak, Z. S. Gribnikov, N. Z. Vagidov, and V.V. Mitin, Appl. Phys. Lett. **75**, 2292 (1999).

[8] R. R. Bashirov, Z. S. Gribnikov, N. Z. Vagidov, and V. V. Mitin, Appl. Phys. Lett. **77**, 3785 (2000).

[9] X. L. Lei, N. J. M. Horing, and H. L. Cui, Phys. Rev. Lett. **66**, 3277 (1991).

[10] J. C. Cao, H. C. Liu, and X. L. Lei, J. Appl. Phys. **87**, 2867 (2000).

[11] J. C. Cao and X. L. Lei, Phys. Rev. B **67**, 085309 (2003)