Field Effects on Picosecond Photoconductive Switch

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ABSTRACT

A new rigorous method which successfully incorporate the ensemble Monte Carlo technique with time-domain finite difference method of solving time varying Maxwell's equations is presented. Interactions between electromagnetic fields and carrier transport properties have been studied and fields effects on picosecond photoconductive switch have been revealed.

A photoconductive switch is a simple device (see Figure 1). Double microstriplines lying on undoped GaAs material with a gap in one of the microstriplines. The microstripline with a gap is biased by a DC voltage source. When shining laser pulse on the gap, such a photoconductive switch would generate electrical waveforms with subpicosecond risetime. Photoconductive device has a lot of applications (1), therefore a thorough understanding of transient processes which also reveal a lot of information about GaAs material properties on a picosecond scale, is desirable.

Our approach to this problem is to solve time varying Maxwell's equations directly and use ensemble Monte Carlo (EMC) technique (2). The ensemble Monte Carlo method has been proved a very useful tool for carrier transport analysis. The principle of ensemble Monte Carlo method is to simulate the motion of carriers in momentum space under the influence of scattering processes and electromagnetic fields. However most of studies in carrier transport often treat fields as constant or other simple approximations. The EMC method is a semiclassical one which is based on Boltzmann transport equation. The nonlinearity of Boltzmann equation makes it very difficult if not possible to consider exact fields in carrier transport study. We use time domain finite difference (TDFD) method [3] to solve time varying Maxwell's equations and TDFD solutions make it easier to combine real fields value with carrier transport results so that we are able to study the field effects on picosecond photoconductive switch which is crucial to the designing and understanding of picosecond switching experiments.

Our calculations are based on a photoconductive switching device in Figure 1. Using Laplace equation

$$\nabla^2 V = 0 \qquad (1)$$

and boundary conditions, the initial potential distribution could be found. Furthermore, using

$$\vec{E}^{o} = -\nabla V \qquad (2)$$

we could find initial electric field.

When laser pulse shines on the surface of the strip gap, there will be a initial carrier distribution according to a decaying exponential. Due to absorption coefficient α, most photogenerated electron-hole pairs will be near surface. A three valley electron and a three band hole model under the effective masses approximation is used for determining the initial energy and momentum $\vec{K}^{0}$ distribution and the starting momentum space distribution is assumed to be isotropic.

Then we follow the EMC program to trace each carrier's movement which is affected by Lorentz force induced by electromagnetic field components in each lattice cubic according to

$$\vec{f}^{t} = q \cdot (\vec{E}^{t} + \vec{\upsilon}^{t} \times \vec{B}^{t}) \qquad (3)$$

When a carrier is in free flight, it follows Newton's second law. Therefore

$$\vec{f}^{t} = \hbar \frac{d\vec{K}}{dt} \cong \hbar \frac{\vec{K}^{t+t_f} - \vec{K}^{t}}{t_f} \qquad (4)$$

where t_f is free flight time.

From equations (3) and (4), we could get $\vec{K}^{t+t_f}$. Then carriers will go through a scattering process. Carrier's momentum will change according to different scattering mechanism. These steps will be repeated until reaching the full time step Δt and we could get carriers states and all other physical quantities of interest. We define current density associated with each lattice cubic as

$$\vec{J}^{t}(i,j,k) = n q \vec{\upsilon}_{avc} = \frac{q\hbar}{\Delta h^3} \sum_{\text{lattice cubic } (i,j,k)} \frac{\vec{K}^{t}(i,j,k)}{m^*} \qquad (5)$$

After EMC calculation we go back to use TDFD algorithm to solve Maxwell's equations and update electromagnetic field values of each lattice cubic. The above procedure is repeated until reach time limit.

Here we present some of our initial results. Fig.2 shows that the constant field assumption leads to a big numerical error. The values of electron velocity of constant field are three times as large as these of real field. Under the influence of initial field, electrons drift to positive side of field. These accumulated charges induce another internal fields which is opposing the initial field. Fig.3 also shows that the conduction current is higher than total current indicating that the displacement current is opposing conduction current and the risetime is about 0.2 picosecond. Thus electron velocity of real field should be lower than that of constant field assumption. In real field case, magnetic field B also tends to decrease the electron velocity. In constant field assumption, B field is neglected. These two factors we believe contribute to inflated electron velocity in constant field assumption. Indeed, the electromagnetic fields in photoconductive switch are extremely uneven and they vary with time and positions. Fig.4 shows Ez component at different times.

In conclusion, we present a new rigorous method which successfully incorporate the ensemble Monte Carlo technique with time-domain finite difference method of solving time varying Maxwell's equations. The interactions between electromagnetic fields and carrier transport properties have been studied rigorously and the transient processes in the picosecond photoconductive switch have been revealed. This method is generally applicable to other ultrafast semiconductor opto-electronic devices.

References

1.D.A.Auston,"Impulse Response of Photoconductors in Transmission Lines," IEEE J. Quantum Electronics, Vol. QE-19, No.4, pp.639-648, April 1983.

2.C. Jacoboni and P. Lugli, "The Monte Carlo Method for Semiconductor Device Simulation," Springer-Verlag Wien New York, 1989.

3.X.Zhang and K.K.Mei,"Time-Domain Finite Difference Approach to the Calculation of the Frequency-Dependent Characteristics of Microstrip Discontinuities," IEEE Trans. on Microwave Theory and Technology, Vol.36, No.12, pp1775-1787, 1988.

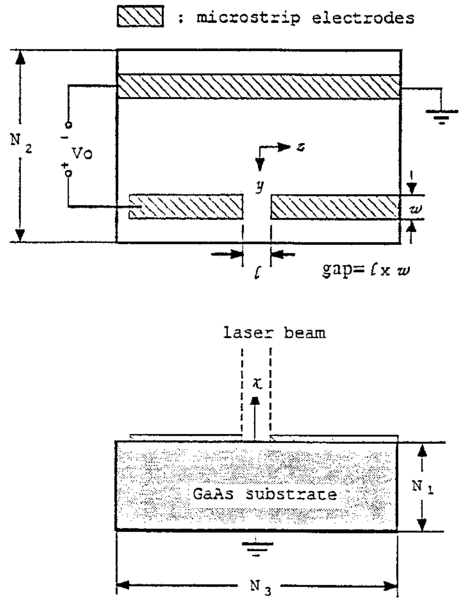

Fig. 1. Photoconductive Switch Structure.

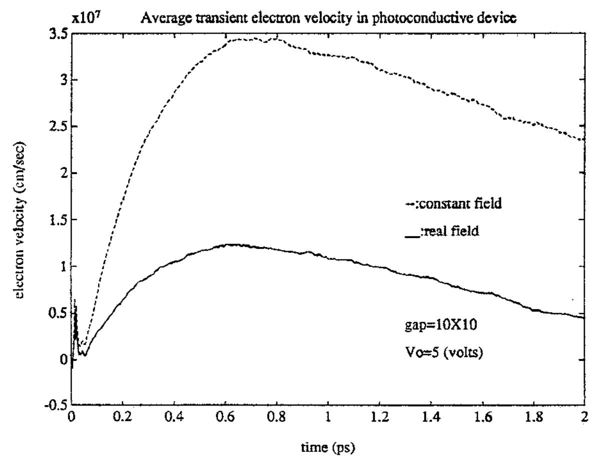

Fig. 2. Electron velocities of real field and constant field assumption.

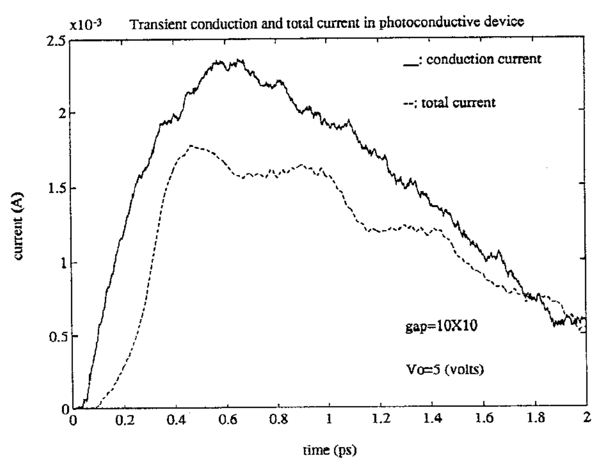

Fig. 3. Transient currents in picosecond photoconductive switch.

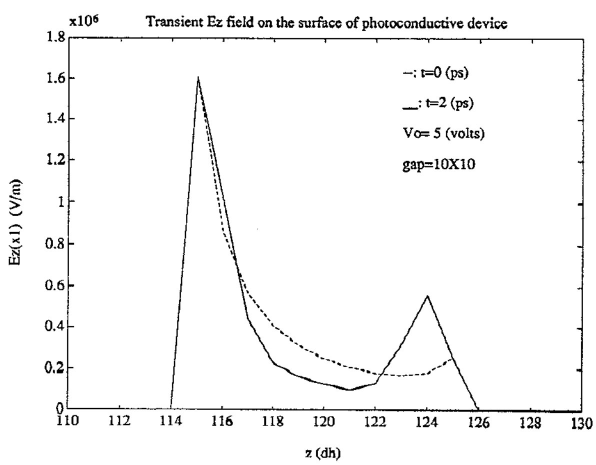

Fig. 4. Ez field on the surface of the device at t=0 (ps) and t=2 (ps).