ELECTRON-ELECTRON INTERACTION EFFECTS ON TRANSIENT TRANSPORT IN SILICON

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Abstract

The effects of electron-electron interactions on the transient electron transport has been investigated using ensemble Monte Carlo method. The expressions for electron-electron scattering rates take into account the ellipsoidal nature of the energy surfaces in silicon. The relative effects of both electron-plasmon and short range e-e interactions strongly depend on the orientation and magnitude of the electric fields. For example, contribution of electron-plasmon scattering is significantly weaker <111> for fields along <111> compared to <100> crystalographic orientations due to strong and rapid heating of electrons in the former case. Additionally, e-e interactions reduce valley repopulation and the transient velocity overshoot in the hot valleys.

I. INTRODUCTION

Electron-electron (e-e) interactions significantly influence the transport dynamics in semiconductors [1-7]. These effects become very critical as the dimensions of the devices shrink requiring highly doped regions to maintain narrower depletion regions which in turn result in very high electric fields. Consequently, there is a need for understanding of the effects of e-e interaction on the transient and steady state transport properties of electrons. Inter-carrier (e-e or hole-hole) interactions involve both momentum and energy transfer between the interacting carriers and as such play an important role in determining the shape of the energy and momentum distributions. For example, strong e-e scattering tends to result in a displaced Maxwellian energy distribution for the carriers [1]. Appel, theoretically examined the influence of e-e scattering on electrical conductivity, thermal conductivity in nonpolar semiconductors and predicted concluded that e-e scattering resulted electrical conductivity and thermal conductivity that were smaller by factors of 0.58 and 0.25, respectively [2]. Furthermore, Asche and co-workers [3] concluded from their experimental measurements on n-doped silicon and theoretical analysis that intervalley e-e scattering was responsible for the decrease of the valley repopulation with increasing concentration. Additionally, Nash and Holm-Kennedy [4] made more extensive measurements of conductivity versus electric field on <111> and <100> crystalographically oriented samples of n-Si with different resistivities at 77 °K to determine the effects of electron-electron scattering on high field transport properties. They used an iterative technique to solve the transport equations, as an improvement over the theoretical model developed by Asche and coworkers, and attributed the observed decrease in the <111> to <100> conductivity with increasing concentration to the intervalley and itravalley e-e scattering.

In this paper we examine effects of e-e scattering on transient transport in silicon using ensemble Monte Carlo method using expressions for e-e scattering rates that into account the ellipsoidal nature of the conduction band valleys [5]. The investigation is carried out assuming at 77 °K and doping concentration of $10^{18} cm^{-3}$ and a constant field of 20 kV/cm. In an earlier paper the effects of changing the magnitude of the field and the doping level were presented. The Monte Carlo method was by first used to investigate the effects of e-e scattering on scattering on velocity overshoot Lugli and Ferry [6] who included both short range e-e interaction and the collective electron-plasmon scattering. However, their investigation was limited to fields along the <111> crystallographic orientation in Si. Unfortunately, for the <111> field orientations electrons in all valleys are heated equally and no valley repopulation occurs and the energy exchange involved in e-e scattering events has a minimal effect. On the other hand, for field orientations along <100> or <110> orientations where the valley repopulation plays an important role on transient and steady state transport, e-e scattering is expected to play a major role in determining the electron transport properties depending on carrier concentration and energies.

II. THE TRANSPORT MODEL

The transient transport of electrons in n-doped silicon was studied using the pair ensemble Monte Carlo (EMC) approach. The EMC model for the Silicon includes all of the ellipsoidal six x-valleys with intervalley f-type phonon scattering between perpendicular valleys, intervalley g-type phonon scattering between parallel valleys, intravalley acoustic phonon scattering, intra- and intervalley e-e, and electron-plasmon scattering, and ionized impurity scattering. The electron-plasmon scattering rates are calculated using the expressions reported by Lugli and Ferry [6]. In our simulation, the cut-off wave vector is .5 times the reciprocal Debye length which is calculated self-consistently using the method proposed by Osman and Ferry [7]. The physical parameters used in the present calculations are the same as those of Brunetti and coworkers [8]. As the transport properties of electrons are determined with respect to the minima of the valleys, there is no distinction between electrons in parallel valleys on the same axis (i.e. they have the effective mass components). This symmetry allows us to consider only three valleys rather than six valleys which reduces the overhead involved in keeping track of electrons in different valleys and in the selection of the final valley following an f-type scattering event.

The EMC method used in this calculation is based on simulating pairs of two electrons' states in parallel which was developed earlier by Hasegawa and coworkers [9]. This approach ensures momentum and energy conservation of the two electrons involved in an e-e scattering event without introducing extra scattering. This is very critical for a realistic assessment of how the energy exchange involved in e-e scattering affects valley repopulation. The details implementing e-e scattering in this EMC approach has been discussed in length by Hasegawa and coworkers [8] and will not be repeated here. In the simulation both intravalley and intervalley (with both electrons remaining in their respective valleys) interactions between electrons are taken into account. The situation in which one or both of the electrons involved in e-e scattering transfer from one valley to another is ignored because at the large momentum exchange involved for such transitions. the differential scattering cross-section for coulomb interactions very small. The expression for e-e scattering rate was given in [5].

III. RESULTS

Figure 1 show the transient population of the cold <001> and hot <010> valleys after the application of uniform electric field 20 kV/cm along <001> crystalographic orientations for electron concentration of $10^{18} cm^{-3}$. In this figure the upper line in each pair of lines represents the population of the cold (001) valley. From this figure it is obvious that plasmon emission has no significant effect on the valley repopulation. However, the emission of plasmons by the fast moving electrons eliminates the energy overshoot of the electrons in the hot valleys as can be seen in Figures 2 (dashed line). On the other hand, short range e-e scattering reduces the transfer rates significantly and leads to a net transfer of energy from the electrons in the hot valleys to those in the cold valleys (see figure 2). The upper line in each pair of lines corresponds to the energy of electrons in the hot (010) valleys in figure 2. These effects were shown to be more pronounced at 10 kV/cm than at 20 kV/cm where the energy lost by the electrons in the hot valleys is compensated by the energy gained from the electric field and higher electron concentrations [5].

In figure 3, the temporal evolution of the energy gain rate of electrons in the (001) valley through e-e and e-plasmon interactions are plotted for two different orientations of the electric field. This shows that the transfer of energy to the (001) valleys from the hot electron plasma is mainly due to the short range two particle intervalley interactions. This transfer is almost an order of magnitude higher than the transfer by absorption of plasmons by the relatively cold electrons. When the orientation of the electric field is changed to <111> direction, the energy gain by the electrons in the (001) valleys is practically zero. This

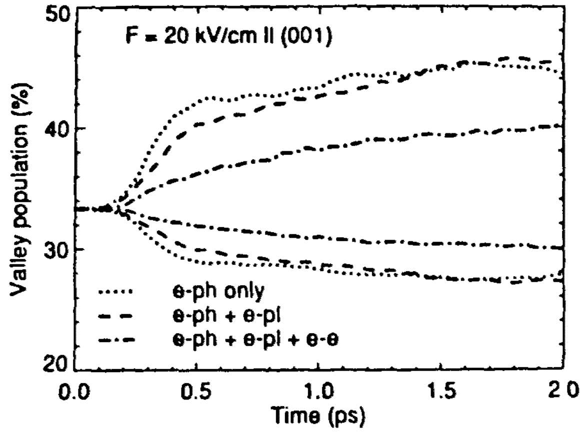

Figure 1: Time evolution of valley population in (100) valleys and (001) valleys for different combinations of scattering processes:

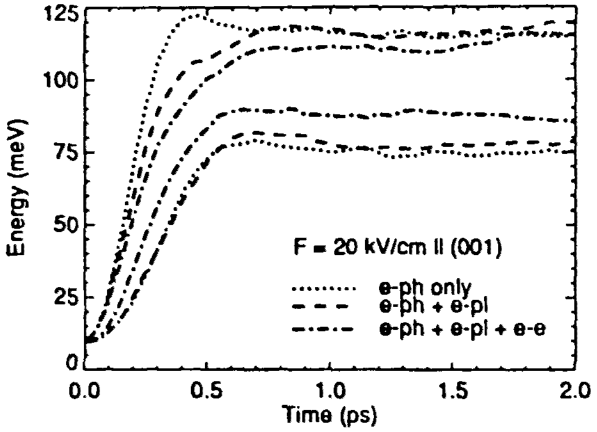

Figure 2: Time evolution of average electron energy in (100) valleys and (001) valleys for different combinations of scattering processes.

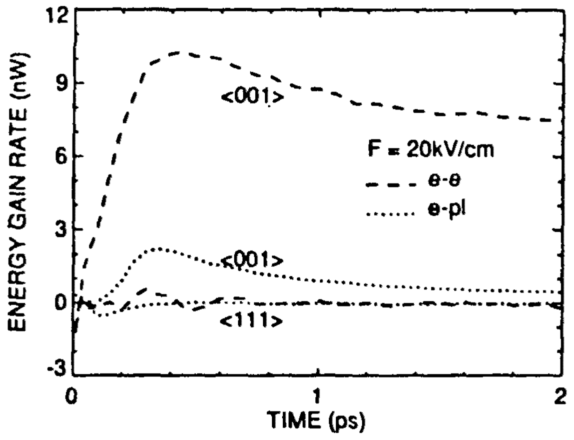

Figure 3: Time dependence of energy gain rates for electrons in the (001) valley through e-e and e-pl interactions for <001> and <111> field orientations.

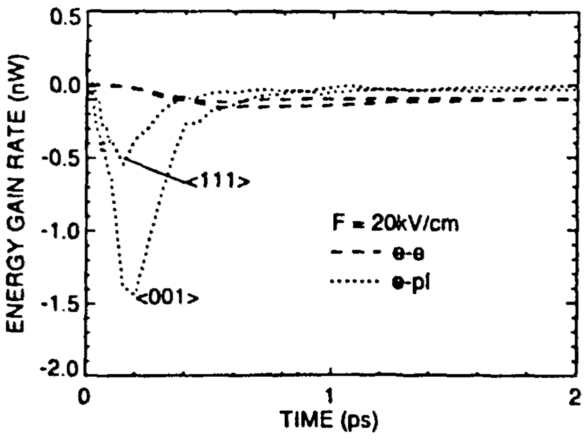

Figure 4: Time dependence of net energy gain rates for electrons in all valleys through e-e and e-pl interactions for <001> and <111> field orientations.

is due to the fact that, for the <111> field orientation the electrons in all valleys are heated equally and as a result e-e scattering distributes the energy equally among the valleys with no preferred direction of energy flow. additionally, the rapid heating of the electrons reduces the screening effects and cut off wavevector for plasmon emission is reduced which reduces the emission rates of plasmons. In figure 4, the net energy gain rates of the electrons in all valleys are shown. Notice, that the net gain from two particle e-e scattering is practically zero because the energy of the particles involved in the scattering is conserved. On the other hand, there is a net energy loss via plasmon emissions mainly during the first 400 femtoseconds after application of the electric field. During this time the electron plasma is relatively cold so that the energy loss through plasmon emission is effective. Changing the field orientation to <111> reduces the energy loss rate by a factor of 3 due the rapid heating of the electrons in this case.

IV. CONCLUSION

We have investigated the effects of short range e-e interaction and collective electron-plasmon interaction on valley repopulation and velocity overshoot in bulk silicon. Our results show that intervalley e-e scattering results in transfer of energy from the hot valleys to the cold valleys for fields along <001> orientation. Furthermore, energy loss rates through plasmon emission are smaller by a factor of 3 for fields along <111> direction compared to <001> direction.

V. ACKNOWLEDGMENT

The authors would like to express their appreciation for helpful discussion with D.K. Ferry. This work was partially supported by NSF through the Center for Design of Analog-Digital Integrated Circuits and National Center for Computational Electronics and utilized the CRAY-YMP system at the National Center for Supercomputing Applications.

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