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Abstract

We performed Monte Carlo simulation of electron response to a strong pumping wave (443 GHz) and weak signal harmonic waves (886 and 1329 GHz) in silicon. A negative dynamic conductivity is found to arise for 1329 GHz above a threshold value of the pumping wave amplitude and below a maximum value of the signal wave amplitude in a limited range of phase difference between the waves.

Key words: Far infrared response, semiconductor, n-Si, wave amplification,
third harmonic generation

I. Introduction

Amplification of small-signal electromagnetic waves at harmonic and incommensurate frequencies has been observed experimentally in n-type GaAs and InSb in the millimeter wave (MMW) range under conditions of electron heating by the pumping wave [1]. Values of the amplification coefficient up to 20 dB have been observed. However, the theory of the phenomenon has not been developed leaving many questions open, e.g., the choice of materials, or lifting the phase limitations, or the problems related to higher operation temperatures and frequencies. Powerful MMW gyrotrons and far infrared (FIR) laser sources of pumping radiation have recently been used for radiation frequency tripling in n-type Silicon [2,3] with the aim of developing a powerful radiation source for plasma diagnostic applications. Numerical calculations have been found to be in excellent agreement with the experiments [4,5] which stimulates interest in the theoretical exploration of wave amplification.

The present work is aimed at calculating the dynamic mobility of n-type silicon in the electric fields of pumping and signal waves by means of Monte Carlo simulations.

II. Problem formulation

Let us consider bulk crystals of n-type silicon represented by six ellipsoidal X-valleys for electrons taking into account the nonparabolicity. At room temperature, the electron intravalley scattering is modeled including one type of acoustic phonons in the equipartition and elastic approximation employing a deformation potential. The intervalley scattering is accounted for by six types of large-momentum zone-boundary phonons (Table 1).

Table 1. Phonon parameters for electron scattering in Silicon, taken from [6]

Phonon type	Phonon temperature [K]	Electron-phonon coupling constant [10^8 eV/cm]
f	220	0.3
f	550	2.0
f	685	2.0
g	140	0.5
g	215	0.8
g	720	11

The Monte Carlo simulation in an alternating electric field follows the standard procedure [7]. The field is supposed to be the sum of the large-amplitude contribution $\mathbf{E}_1\cos \omega t$ and the small-amplitude of the n-th harmonic field $\mathbf{E}_n\cos(\omega_n t + \phi)$. The field is assumed to be parallel to <100>-axis. The time dependence of electron drift velocity is calculated for given values of amplitudes and the angular frequencies ω_1 and ω_n, as well as the phase shifts ϕ. A Fourier-transform procedure is applied next in order to obtain the drift velocity components $v_1\cos(\omega_1 t + \psi_1)$ and $v_n \cos(\omega_n t + \psi_n)$ where $\psi_{1,n}$ are the drift velocity phases. The complex dynamic conductivity $\sigma = en\mu$ is just the product of the electron concentration n, the elementary charge e, and the complex mobility μ. The latter is determined as $(v_n/E_n)\exp i(\psi-\phi)$.

III. Results and discussion

The dynamic mobility at the third harmonic frequency is found to depend on the phase shift of the signal wave φ (Fig.1). The dependence is oscillatory, in agreement with experimental observations.

The dependence of the electron mobility for the third harmonic wave on the pumping wave amplitude is shown in Fig.2. In order to get a negative mobility a threshold value of the pumping wave amplitude has to be overcome. The absolute value of the real part of the dynamic mobility increases with the pumping wave amplitude.

The negative dynamic mobility is found to diminish with the rise of the signal wave amplitude (Fig.3). The imaginary part of the mobility is phase- and amplitude-dependent indicating an interplay between the inductive and capacitive behavior of the free-carrier system.

The dynamic mobility at the second-harmonic frequency is presented in Fig.4. It depends on the phase shift φ periodically but the mobility oscillates now 2 times within the range of $\varphi=0$ - 2π when there is no steady state electric field ($E_0=0$). In this case the mobility does not go through zero in the whole range of phase shifts. The symmetry of the free-electron system is reduced in the steady state electric fields. The real part of the mobility at the second harmonic frequency becomes negative in certain ranges of the phase shifts (Fig.4). The imaginary part of mobility is phase- and amplitude-dependent indicating an interplay between the inductive and capacitive behavior of the free-carrier system. Apart from this, the steady-state drift of electrons is seen to arise (Fig. 5) due to the fundamental- and the second harmonic wave mixing even in the absence of dc electric fields.

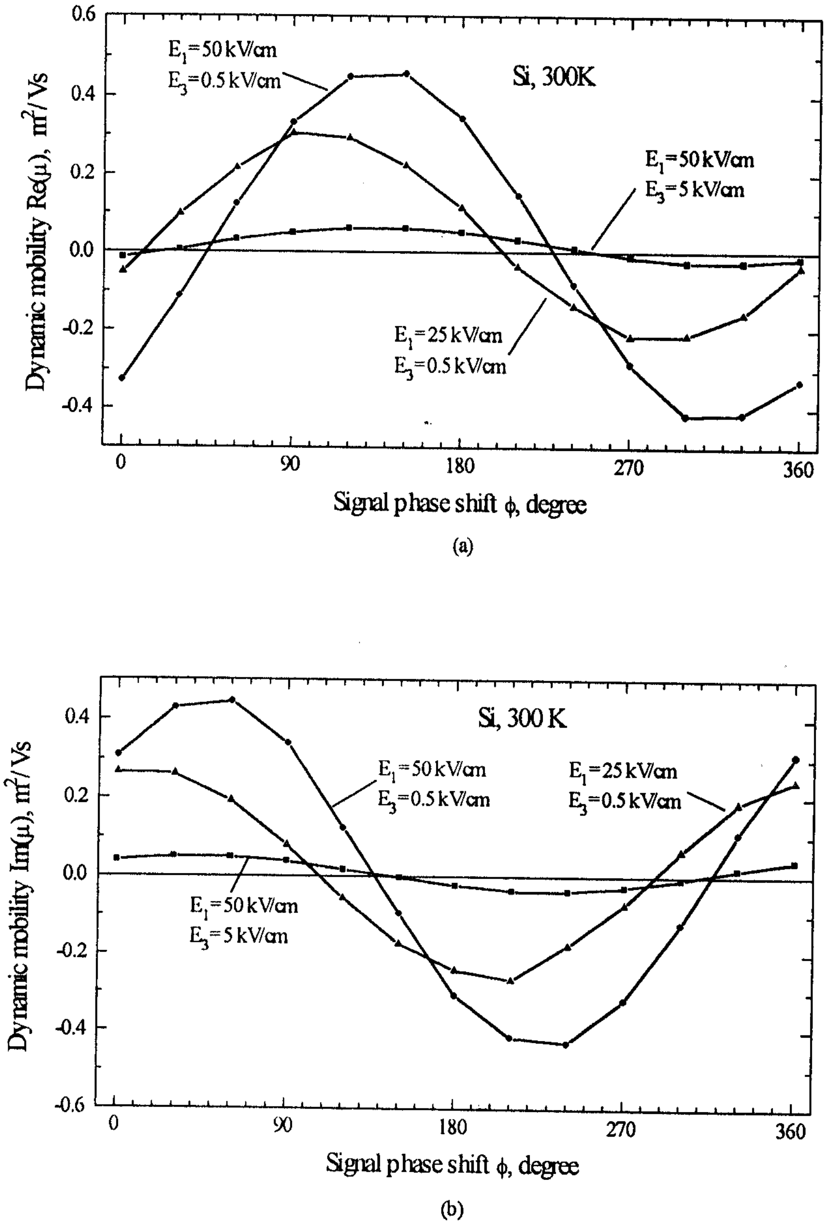

Fig.1. The real (a) and imaginary (b) parts of the dynamic mobility at 1329 GHz for electrons in silicon as function of the signal wave phase shift with respect to the pumping wave (443 GHz). The field amplitude values are shown in the figure.

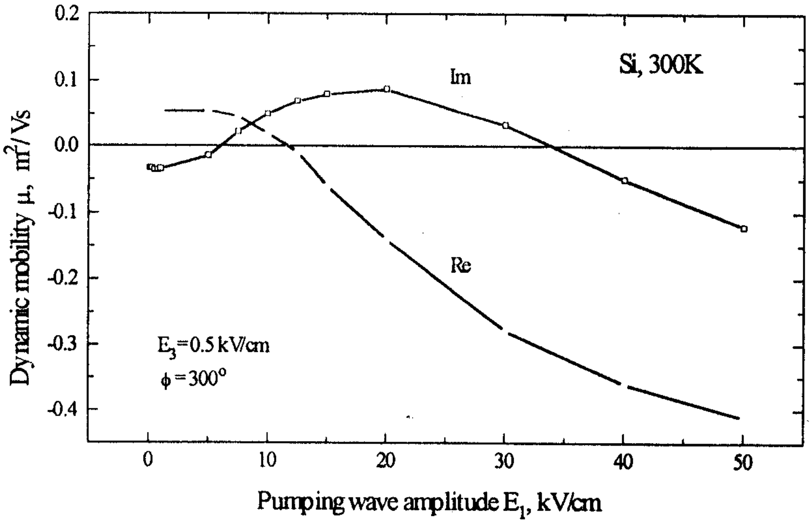

Fig.2. The real and imaginary parts of the dynamic mobility at 1329 GHz for electrons in silicon as function of the pumping wave amplitude. The signal wave amplitude and phase is shown in the figure. The pumping wave frequency is f = 443 GHz.

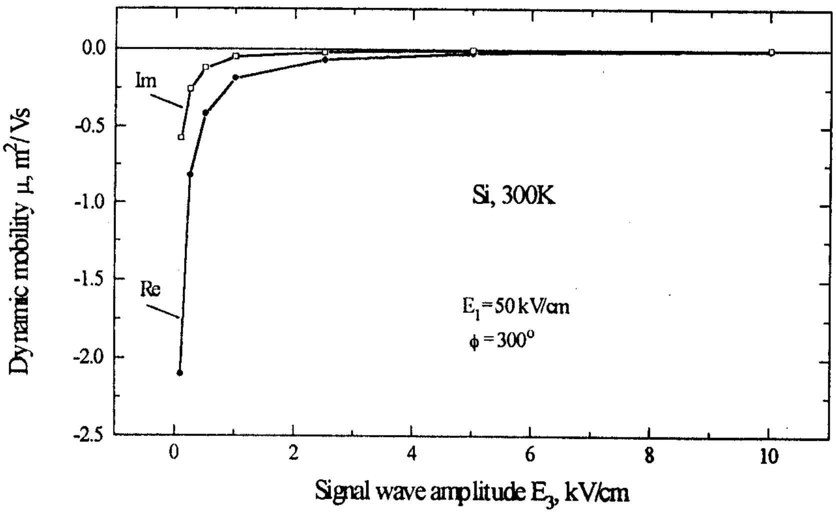

Fig.3. The real and imaginary parts of the dynamic mobility at 1329 GHz for electrons in silicon as function of the pumping wave amplitude in the presence of the pumping wave (443 GHz). The pumping wave signal amplitude and phase is shown in the figure.

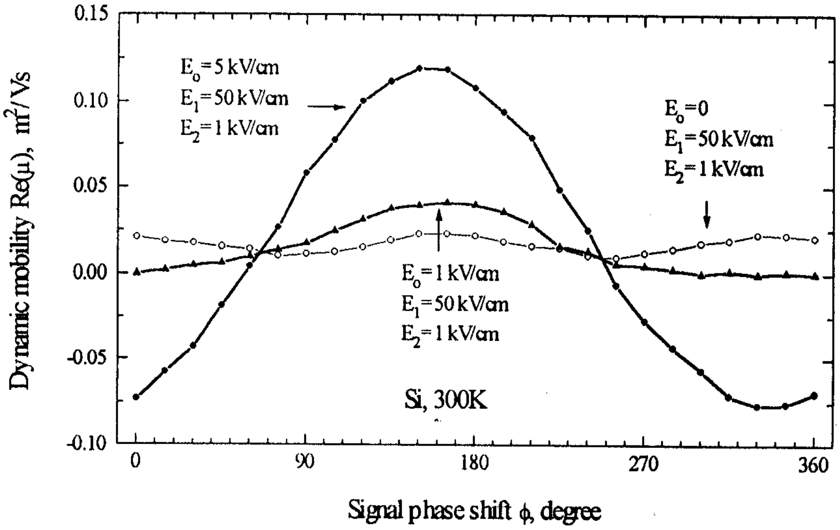

Fig.4. The real part of the dynamic mobility at 886 GHz for electrons in silicon as function of the signal wave phase shift in the presence of the pumping wave (443 GHz) and the steady state electric fields. The field values are shown in the figure.

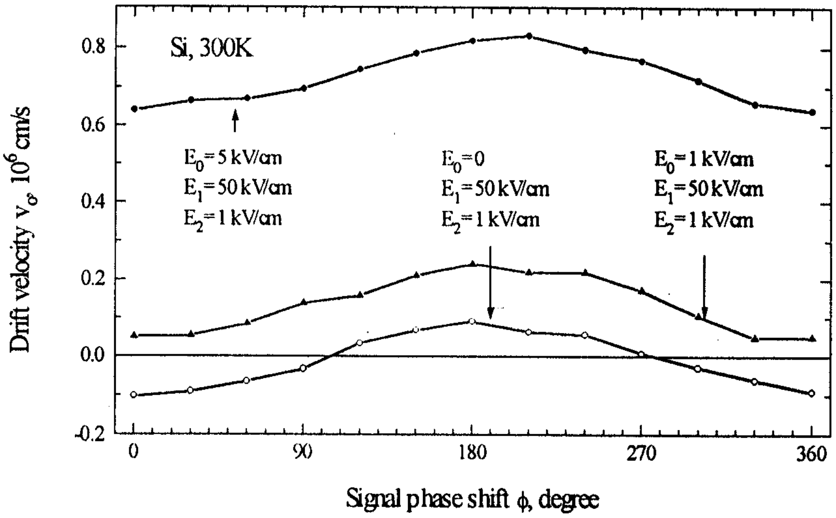

Fig.5. Steady state drift velocity as function of the signal phase shift. The pumping wave amplitude E_1 and the signal one E_2, as well as the dc field E_0 are shown in the figure.

IV. Conclusions

The dynamic mobility for the second harmonic wave in n-type silicon subjected to coherent pumping infrared radiation does not show any possibility of wave amplification in the absence of the steady state electric fields. The only effect of the signal- and pumping wave mixing is the nonlinear rectification. The negative dynamic mobility arises when the steady state electric field is present.

The dynamic mobility for the third harmonic wave gives rise to wave generation and amplification in silicon subjected to coherent pumping with infrared radiation without the steady state fields.

The wave generation is naturally observed in the form of the harmonic emission. The amplification requires the presence of an incident phase-controlled harmonic wave and is awaiting experimental verification in the far infrared range. It is expected that the output harmonic wave intensity in this case will be enhanced in a certain range of the input phase difference with respect to the intensity obtained in ordinary harmonic generation experiments.

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References

1. Ambrazevièienë V., Brazis R. and Kunigëlis A., in: *Nonlinear Surface Electromagnetic Phenomena, Ponath H.-E. and Stegeman G.I. Eds*, Elsevier Sci. Publ.B.V., North-Holland, Chapt. 6, p.417 (1991).

2. Keilmann F., Brazis R., Barkley H., Kasparek W., Thumm M. and Erckmann V., Europhysics Letters, **11** (4), p.337 (1990).

3. Urban M., Nieswand Ch., Siegrist M.R., and Keilmann F., J. Appl. Phys, **77**, p.981(1995).

4. Urban M.,.Siegrist M.R, Asadauskas L., Raguotis R. and R.Brazis, Lithuanian Journal of Physics, **35**, p.430 (1995).

5. Urban M., Siegrist M.R., Asadauskas L., Raguotis R. and Brazis R., Appl. Phys. Letters, **69**, p. 1776 (1996).

6. Brunetti R., Jacoboni C., Nava T., Reggiani L., Bosman G., Zijlstra R.J.J., J.Appl.Phys., **52**, p.6713 (1981).

7. Lebwohl P.A, J. Appl. Phys. 1979, **44**, p.1744 (1979).