EDISON 16 IOP Publishing
Journal of Physics: Conference Series **193** (2009) 012091 doi:10.1088/1742-6596/193/1/012091

Plasmonic noise in Si and InGaAs semiconductor nanolayers

J. Pousset[1], J.-F. Millithaler[1], L. Reggiani[1], G. Sabatini[2], C. Palermo[2], L. Varani[2], J. Mateos[3], T. González[3], S. Pérez[3], A. Bournel[4] and P. Dollfus[4]

[1] Dipartimento di Ingegneria dell'Innovazione and CNISM, Università del Salento, Via Arnesano s/n, 73100 Lecce, Italy

[2] Institut d'Électronique du Sud, UMR CNRS 5214, Université Montpellier II, place Bataillon, 34095 Montpellier Cedex 5, France

[3] Departamento de Física Aplicada, Universidad de Salamanca, Pza. Merced s/n 37008 Salamanca, Spain

[4] Institut d'Électronique Fondamentale, UMR CNRS 8622, Université Paris-Sud, 91 405 Orsay Cedex, France

E-mail: `jeremy.pousset@unile.it`

Abstract. By Monte Carlo simulations we investigate the spectrum of voltage fluctuations of Si layers of variable thickness W in the range $2 \div 100$ nm and variable length L in the range $10 \div 1000$ nm embedded in an external dielectric medium. Calculations are performed at T = 300 K for different doping levels and in the presence of an external bias of increasing strength. For $W \geq 100$ nm and carrier densities of 5×10^{17} and 5×10^{18} cm^{-3} the peaks agree with the value of the three dimensional (3D) plasma frequency. For $W \leq 10$ nm the results exhibit a plasma frequency that depends on L, thus implying that the oscillation mode is dispersive. The corresponding frequency covers a wide range of values $0.2 \div 10$ THz and is in agreement with the values predicted by existing analytical models. At sufficiently high bias the 2D plasma peak is washed out and we observe the onset of a peak in the subTHz region which, by analogy with the results obtained in n-InGaAs layers, is associated with transit time instabilities induced by current saturation conditions.

1. Introduction

Generation and detection of electromagnetic radiation in the TeraHertz (THz) domain is a subject in fast development because of its potential applications in different branches of advanced technologies, such as broad-band communications and high-resolution spectroscopy [1, 2]. As a consequence, the realization of affordable solid-state devices operating in the THz domain at room-temperature and with compact, powerful, and tunable characteristics is a mandatory issue. To this purpose, one of the most promising strategies lies in the plasmonic approach which exploits the plasma frequency of free carriers as a possible mechanism for detection/generation [3]. In this framework, through an analytical approach, the case of a two-dimensional (2D) electron layer constituted by the ungated channel of a nanometric transistor was considered in Ref. [4]. Moreover nanometric Si transistors have shown their ability to detect THz radiation using plasma waves [5]. The aim of this work is to investigate the same problem from a microscopic point of view thus testing the limits of applicability of the analytical approach and exploiting possible implementations. Previous theoretical studies have shown the presence and the main properties of electron plasma in InGaAs layers [6]. Although electron mobility in Si is about a factor of ten lower than in InGaAs, Si technology is more mature and its industry has a leading role. Therefore, here we mainly focus on electron plasma in Si layers. To this purpose, we consider an n-type Si layer, embedded in a symmetric dielectric, in the presence of an external bias of arbitrary strength and analyse the frequency spectrum of voltage fluctuations obtained from a Monte Carlo simulator coupled with a 2D Poisson solver

2. Models and results

The analytical model considers a 2D sheet of electrons, under collisionless conditions, in the $\vec{r} \equiv xy$-plane embedded in a dielectric along the z direction and leads to a dispersive 2D plasma frequency [4]

$$f_{2D} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_{2D}|\mathbf{k}|}{2\ m_0\ m\ \varepsilon_0\ \varepsilon_{diel}}} \qquad (1)$$

where $|\mathbf{k}|$ is the modulus of the wavevector in the k_x,k_y plane, m_0 and m the free and effective electron masses, respectively, n_{2D} the 2D carrier density, e the electron charge, ε_{diel} the relative dielectric constant of the outside dielectric, and ε_0 the vacuum permittivity. We notice that the 2D plasma frequency is dispersive (i.e. k dependent) and depends on the external dielectric.

Plasma waves also exist in bulk (3D) and their dispersionless frequency is

$$f_{3D} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_{3D}}{m_0\ m\ \varepsilon_0\ \varepsilon_{mat}}} \qquad (2)$$

with n_{3D} the 3D carrier density and ε_{mat} the relative dielectric constant of the bulk material.

The numerical investigation of this problem is carried out by using a microscopic Monte Carlo approach coupled with a 2D Poisson solver. By evaluating the fluctuations of the voltage around its steady-state value in the center of the device, we calculate the spectral density of this quantity from the corresponding correlation function and look for its spectrum. We consider doped layers of Si and InGaAs at 300 K in which the spectral density exhibits a peak in the THz range. This peak is analyzed as function of geometrical parameters, doping concentration and applied voltage. To this purpose we take lengths L in the range $10 \div 1000$ nm, thicknesses W in the range $1 \div 100$ nm and carrier densities of 5×10^{17} and 5×10^{18} cm^{-3}. The layers are surrounded by a 10 μm-thick dielectric (SiO_2). For the case of Si, scattering with impurities is neglected.

2.1. Thermal equilibrium

Figure 1 reports for the case of Si the frequency of the plasma peaks as a function of L for different widths and a carrier density of 5×10^{18} cm^{-3}. Symbols refer to calculations and lines to the theoretical 3D and 2D values for widths of 2 and 10 nm, respectively. For a width $W = 100$ nm, the frequency of the observed peak corresponds to that of the 3D plasma frequency. Because of its ellipsoidal manyvalley band structure, by neglecting nonparabolic effects the electron effective mass is given by: $m = \left[3m_l^{-1}m_t^2/(m_t + 2m_l)\right]^{2/5}$, with m_t the transverse component and m_l the longitudinal one. For the cases of the two thinnest layers, the frequency of the peak is found to decrease as the square root of the length. Furthermore, the frequency increases as the square root of the width. Both dependences are actually predicted by Eq. (1) when taking $n^{2D} = n_{3D} \cdot W$ and $k = \pi/2L$.

Figure 2 reports the frequency of the peaks as a function of the layer length for two carrier densities of 5×10^{17} and 5×10^{18} cm^{-3}, respectively, and a width $W = 10$ nm . The theoretical values of the respective 2D frequencies are also reported. Here the frequency of the peak is

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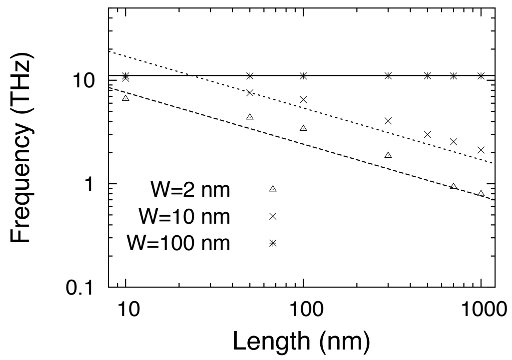

Figure 1. Frequency of the peak present in the spectral density of voltage fluctuations as a function of the layer length, whose carrier density is $n_{3D} = 5 \times 10^{18}$ cm^{-3}. Lines refer to theoretical 3D plasma frequency (solid line) and 2D plasma frequencies for $W = 2$ nm (dashed line) and 10 nm (dotted line), respectively.

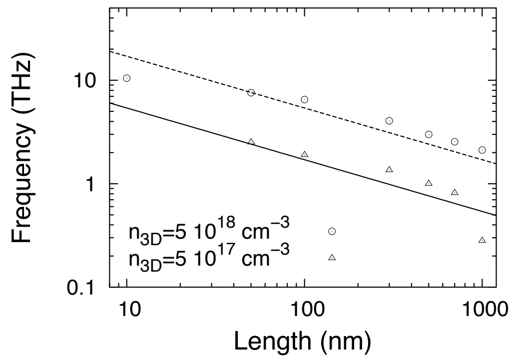

Figure 2. Frequency of the peak present in the spectral density of voltage fluctuations as a function of the layer length for $W = 10$ nm and for the reported carrier densities. Lines refer to the 2D plasma frequencies for $n_{3D} = 5 \times 10^{17}$ (solid line) and 5×10^{18} cm^{-3} (dashed line), respectively.

found to increase as the square root of carrier density in agreement with Eq. (1). Therefore, the presence of 2D and 3D plasma waves in Si layers has been evidenced through microscopic simulations and the dependences from geometric parameters and carrier density have been pointed out.

By simulating Si layers with W in the range $1 \div 150$ nm, $L = 100$ nm and a carrier density of 5×10^{18} cm^{-3}, we have investigated the cross-over between the 2D and 3D plasma peaks, which is found to be well described by the simple expression $f = f_{3D} f_{2D}/(f_{3D} + f_{2D}) = f_{3D}[\sqrt{W}/(\sqrt{W_0} + \sqrt{W})]$ with $W_0 = 4\varepsilon_{diel} L/(\pi \varepsilon_{mat}) = 44$ nm, the width of the cross-over.

2.2. Ohmic and saturation regime

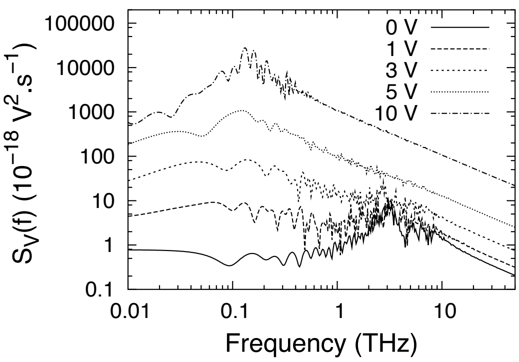

Figure 3. Spectral densities of voltage fluctuations in a Si layer with $n_{3D} = 5 \times 10^{18}$ cm^{-3}, $W = 10$ nm and $L = 1$ μm for different applied voltages.

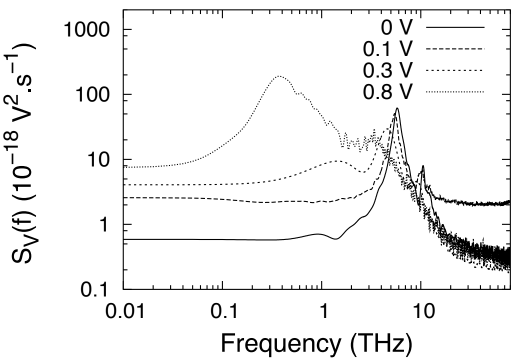

Figure 4. Spectral densities of voltage fluctuations in an InGaAs layer with $n_{3D} = 10^{18}$ cm^{-3}, $W = 1$ nm and $L = 500$ nm for different applied voltages.

We consider now the plasma peak as a function of an applied voltage and compare the case of n-Si with that of similar n-InGaAs structure. To study the transition from Ohmic to saturation regime, Fig. 3 reports the spectral density of voltage fluctuations S_V extracted in the middle of Si layers for several applied voltages. At low bias, the peak related to the 2D plasma waves is recovered. At increasing voltages, the position and amplitude of this peak remains practically constant whereas the low frequecy plateau of the spetrum, related to diffusion noise, increases until the plasma peak is completely suppressed. At the highest voltage the onset of another peak is observed in the sub-THz region for a frequency which is found to scale as the inverse of L. The existence of this peak seems to be related to the presence of voltage oscillations induced by transit time effects coming from current saturation conditions. Figure 4 reports the results for the analogous case of an n-$In_{0.53}Ga_{0.47}As$ layer. Again, at increasing voltages the low frequency plateau of the spectrum starts increasing while the amplitude of the plasma peak remains practically constant. Then, because of the onset of negative differential mobility conditions, the spectrum exhibits the onset of a peak which is precursor of the establishment of current oscillations due to periodic travelling of the associated Gunn domains.

3. Conclusions

Through Monte-Carlo calculations of the spectral density of voltage fluctuations we investigated THz oscillations in Si nano-layers embedded in an external dielectric as a function of geometry, carrier density, and strength of applied voltage. The microscopic investigation of the characteristic frequency peaks of the voltage fluctuations evidences a rich scenario, only partially predicted by the exisisting 2D analytical model [4]. Under thermal equilibrium and Ohmic conditions, the results of simulations show that for thick layers, i.e. W above 100 nm, 3D plasma oscillations appear independently of channel length, thus confirming an analogous study carried out in InGaAs [6]. By contrast, for thin layers, i.e. W below 100 nm, we observed the transition from 3D to 2D plasma modes where the 2D plasma frequency decreases with increasing channel length in agreement with the predictions of the analytical model [4]. Under saturation conditions, the results of simulations show that the low frequency plateau of the spectrum, related to diffusion noise, totally covers the plasma peak and another peak, probably related to transit time effects of some instability induced by current saturation, appears at sub-THz frequencies. The analogous case of InGaAs layers evidences the same behaviour, with Gunn oscillations, associated with negative differential mobility, washing out completely plasma waves. The work was supported by: CNRS - GDR and GDR-E projects "Semiconductor sources and detectors of THz frequencies", "Ministère des affaires étrangères et europénnes" through a "Lavoisier" grant (J. Pousset), Region Languedoc-Roussillon - project "Plate-forme Technologique THz", the Dirección General de Investigación (MEC, Spain), FEDER through the project TEC2007-61259/MIC, Accion Integrada HF2007-0014 and by the Consejería de Educación of the Junta de Castilla y León (Spain) through the project SA019A08 and GR270.

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