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Study of Current-Mode Noise of $Si_{1-x}Ge_x$/Si Strained Heterojunctions

M. J. Martín[1]), D. Pardo, and J. E. Velázquez

Dpto. de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n, ES-37008 Salamanca, Spain[2])

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A one-dimensional Monte Carlo study of noise properties of p-$Si_{1-x}Ge_x$/n^+-Si submicron heterojunctions is presented. An attempt is made to understand the noise performance of the diodes by examining and comparing the spectral density of current fluctuations ($S_I(f)$) for different Ge profiles. Special attention is given to investigating the role of each type of carrier in different regions of the device. It is important to identify the origin of the very high values of $S_I(f)$ found in the heterojunction with an abrupt Ge profile equal to 0.3 for the 0 to 1000 GHz range. In a graded heterojunction, $S_I(f)$ decreases as consequence of a more effective current control by the barrier in agreement with the shot nature of the low frequency noise.

Introduction. During the past few years, structures based on the pseudomorphic $Si_{1-x}Ge_x$ strained layer on Si system have had a considerable impact in the improvement of the heterostructure bipolar transistor (HBT) performance [1]. The HBT technology has allowed the cutoff frequency to be extended into the millimetre-wave region. Therefore, in order to design new high speed and low noise devices the noise phenomena at high frequency must be adequately understood. This paper focuses on the device physics and noise behaviour of Si/$Si_{1-x}Ge_x$ n^+p heterojunctions with constant and graded distribution of the Ge content in the p region.

Results. The typical thickness of the base region of an HBT lies in the submicron range and hence the carrier transport is non-stationary. In view of this, our study was carried out using an ensemble Monte Carlo algorithm self-consistently coupled to a Poisson solver [2]. We consider three structures: a pn^+ (Si) homojunction (D1), a p-$Si_{0.7}Ge_{0.3}$/n^+-Si heterojunction (D2) and a p-$Si_{1-x}Ge_x$/n^+-Si gradual heterojunction (D3). Fig. 1 shows the geometry, the doping levels, the Ge profile (x) and the band diagram of the three devices. In D3 we assume a linear variation of x from 0 to 0.3. The SiGe layers are taken to be strained despite their non-realistic dimensioning to facilitate comparison of the results obtained for D2 and D3 with those obtained for D1, previously reported elsewhere [3]. The model does not include generation–recombination processes. The band discontinuities are 30 meV for the conduction band and 260 meV for the valence band [4].

Fig. 2 shows the spectral density of current fluctuations (S_If)) in all the structures for several forward bias values. On comparing the results for D2 with those for D1, the

[1]) Presently on leave at DIMES, Delft, The Netherlands.

[2]) Fax: +3423294584; e-mail: mjesus@rs6000-usal.es

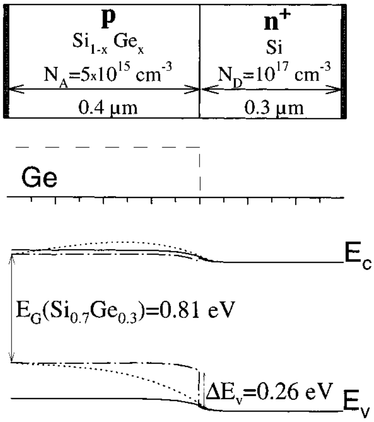

Fig. 1. Geometry, doping levels, germanium profile and band diagram under forward bias conditions. Solid line: D1, dashed line; D2, dotted line: D3

most remarkable effect is a sharp increase of $S_I(f)$ in the 0 to 1000 GHz range. A displacement of the low-bias maximum of $S_I(f)$ (related to the electron plasma fluctuations in n^+ [3]) towards a frequency close to 500 GHz when the bias increases (specially for bias values above the built-in potential: high injection regime) is also seen. In order to deeply understand this response, the different factors contributing to $S_I(f)$ of D2 were studied (Fig. 3). It was concluded that the increase of $S_I(f)$ with the bias in the 0 to 500 GHz range is supported by electron current fluctuations in the SiGe region. This agrees with the accumulation of minority carriers (electrons) in the low doping region (SiGe) in the high-injection regime. This electron accumulation (largely supported by the band discontinuity) also leads to coupling between the fluctuations of the electron and hole currents (see plots for 0.90 V bias, Fig. 3).

The most important effect of the Ge grading is the pronounced decrease of $S_I(f)$ in D3 relative to D2. Furthermore, in D3 excess noise is not found for bias as high as 1.0 V, nevertheless, in D1 and D2 significant excess noise is found for bias lower than 0.90 V. This means that both D2 and D3 heterostructures exhibit very different low-frequency behaviours in their spectral density of current fluctuations $S_I(0)$. For a more complete evaluation, $S_I(0)$ versus the total current density (I_T) across the diodes in the

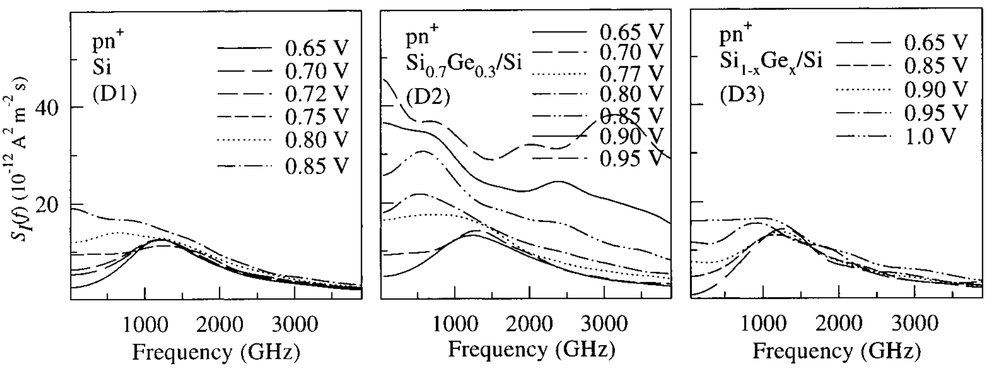

Fig. 2. Spectral density of current fluctuations $S_I(f)$ for the homojunction D1 (left), abrupt heterojunction D2 (centre) and graded heterojunction D3 (right) for several bias values

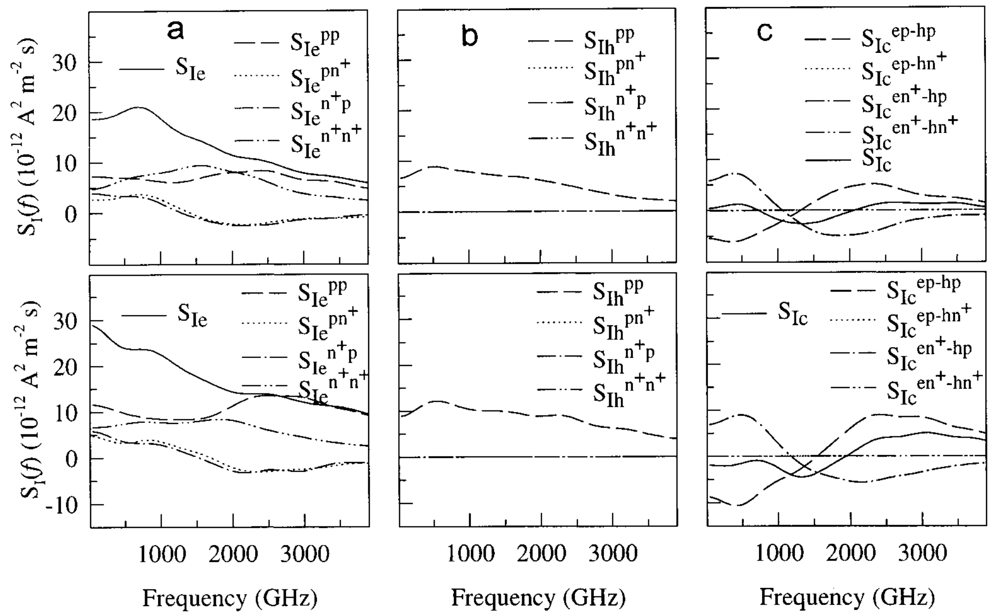

Fig. 3. Contributions to $S_I(f)$ of spectral density of current fluctuations of a) electrons b) holes and c) crossed in D2 for 0.80 V (upper plots) and 0.90 V bias (lower plots). In a) and b) the super-indexes in S_{Ie} or in S_{Ih} indicate the regions (n^+ or p) involved in the calculation of the correlations. In c), S_{Ic}^{iy-jz} represents the cross-contribution to $S_I(f)$ between "i" type (electron or hole) carriers inside the "y" region and to the "j" type or carriers belonging to the "z" region

different structures was compared (Fig. 4). The behaviour of $S_I(0)$ for D2 is similar to that of D1. In particular, three regions: shot noise, thermal noise and an excess noise have been found [3]. Nevertheless, in the whole range of current density D3 exhibits a $2qI_T$ dependence (shot noise) due to the effective barrier control.

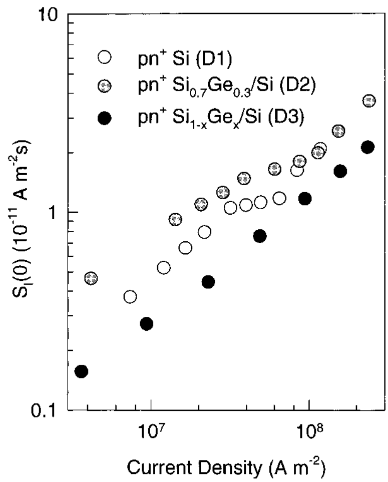

Fig. 4. Low-frequency spectral density of current fluctuations $S_I(0)$ as a function of the total density current flowing through the diodes

Conclusions. The study of noise properties of $pn^+Si_{1-x}Ge_x$/Si heterojunctions, abrupt and graded, has been performed using a one-dimensional Monte Carlo simulator. We conclude that in the abrupt heterojunction the fluctuations of the electron current in the low doping region are responsible for the high values of $S_I(f)$ in the 0 to 1000 GHz range. Also, ion the high-injection regime the accumulation of minority carriers in the SiGe region leads to an abrupt increase in $S_I(f)$. The $S_I(f)$ response strongly depends on the Ge profile, when we consider the graded heterojunction $S_I(f)$ is small in comparison with the abrupt heterojunction as a consequence of a more effective current control by the barrier. In fact, we find for D3 a shot noise behaviour of $S_I(0)$ throughout the current density range.

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