Spatial Dependence of the Phonon-Limited Mobility in Arbitrarily Oriented Si-Nanowires

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INTRODUCTION

The study of the transport properties of Si-Nanowires (NWs) is a research field of high interest [1], [2]. The spatial dependence of the phonon-limited mobility (μ_{ph}) and, in particular, the role of the corners has recently been assessed by Lee et al. [3] through the development of a Spatial Dependent Mobility (SDM) expression. However, only (100)/[011] NWs were considered in their study. In this work, we extend their approach to analyze the SDM of arbitrarily oriented square NWs.

RESULTS AND DISCUSSION

NWs with SiO_2 as gate insulator (T_{ins}=1nm), midgap metal gate, undoped body and width $W_{Si} \geq$ 5nm are considered. For these sizes, the effective mass (EM) approach provides accurate enough results [4]. Only μ_{ph} (both acoustic and optical phonons) is considered, and the mobility is calculated through the Kubo-Greenwood formula [2]. The SDM is studied by means of two expressions (Fig. 1). The first one (SDM) was presented in [3], while in this work we propose an alternative (SDM2) which combines the information provided by the SDM with the actual population of each device region. Fig. 2 shows the SDM for NWs with W_{Si} = 10nm. Three orientations are considered: (100)/[001] (first row), (110)/[001] (second row) and (01$\bar{1}$)/[011] (third row). First column figures were calculated using (1). The results for (100)/[001] are similar to those shown in [3]. As for (110)/[001] and (01$\bar{1}$)/[011] NWs, the SDM is strongly correlated to the directions where the valleys with lowest conduction EM (Δ_4 and Δ_2, respectively) get the highest confinement EM and thus the largest population. A complementary vision of these results can be found when using (2) (second column): the SDM2 is higher at the corners of the NWs due to their larger electron density (ED). This effect is more noticeable in (110)/[001] NWs due to: *(i)* the higher SDM of the corner regions (Fig. 2(c)) and *(ii)* the larger ED near the corners. Fig. 3 shows the results for NWs with W_{Si} = 5nm, where more homogeneous mobilities are achieved for the SDM, while the SDM2 grows at the center of the NWs. For both expressions, the largest values are attained by the (110)/[001] NW. Fig. 4 compares the contribution to the SDM2 of the first two subbands of the [100] valley (red in the inset) for (100)/[001] and (110)/[001] NWs. As shown, the contribution of the first subband in the (110)/[001] device is higher, being responsible for the SDM2 increase near the center of the device. Fig. 5a shows $\mu_i \times n_i$ of each subband, which measures its relative contribution to the total mobility. For a wide range of charge density per unit length (N_i) values, only the first subband of Δ_4 valleys significantly contribute to the mobility in (110)/[001] NWs while also the second subbands are relevant in (100)/[001] devices (which is consistent with the result shown in Fig. 4). Fig. 5b compares the acoustic-phonon momentum relaxation time (τ_i^{ac}) for these two subbands at V_G = 0.8V (optical phonons are not considered to simplify the analysis [3]). As shown in the inset (where the rest of the components in the Kubo-Greenwood formula are depicted), only energy values below 0.15eV effectively contribute to the mobility. Thus, the smaller mobility achieved by the first subband of (100)/[001] NW is due to the reduction in τ_1^{ac} in this range of energies, caused by its higher energetic proximity to the second subband. Since the mobility of the first subband governs the behavior of these small devices, (110)/[001] NWs achieve the highest μ_{ph} for W_{Si} = 5nm NWs (dashed-diamonds in Fig. 5c). For larger devices the analysis is more complex, as more subbands contribute to the mobility. However, the subband energy separation of Δ_4 valleys (not shown) is smaller for the (110)/[001] NW [5], reducing the mobility of the first subbands and thus lowering μ_{ph} (solid-diamonds in Fig. 5c).

ACKNOWLEDGMENT

Work supported by the projects P09-TIC-4873, FIS-2008-05805 and FIS-2011-26005. E. Gonz´alez-Marín also acknowledges the FPU program.

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$$SDM(x,y) = \frac{\sum_i |\Psi_i(x,y)|^2 \mu_i n_i}{\sum_i |\Psi_i(x,y)|^2 n_i} \quad (1)$$

$$SDM2(x,y) = A \times \frac{\sum_i |\Psi_i(x,y)|^2 \mu_i n_i}{\sum_i n_i} \quad (2)$$

Fig. 1. SDM and SDM2 definitions. Ψ_i, μ_i and n_i are the i-th subband wave function, mobility and population, respectively, and A is the device area.

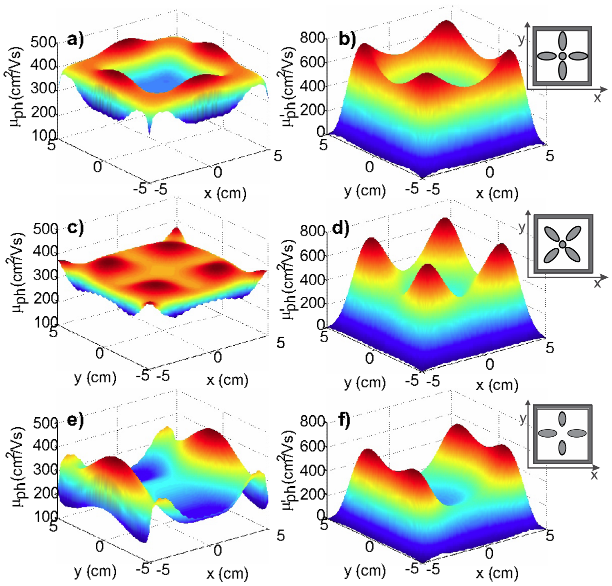

Fig. 2. SDM (left column) and SDM2 (right column) of NWs with $W_{Si} = 10$nm and $V_G = 0.8$V. (a) and (b): (100)/[001], (c) and (d): (110)/[001] and (e) and (f): (01$\bar{1}$)/[011] (see insets).

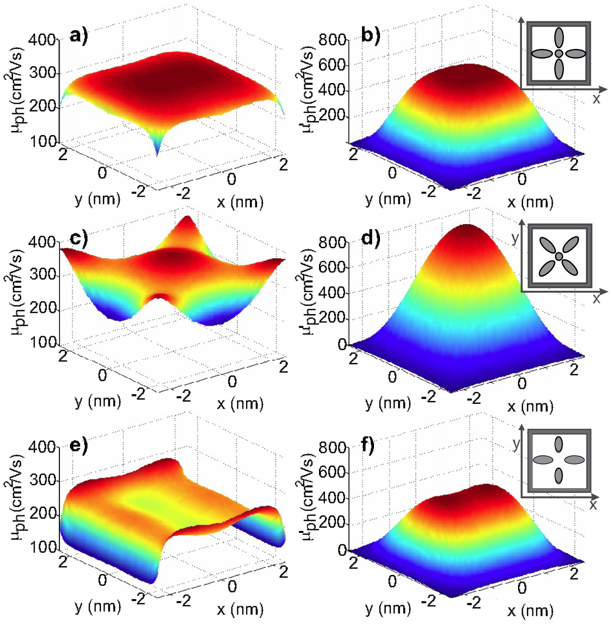

Fig. 3. SDM and SDM2 of NWs with $W_{Si} = 5$nm and $V_G = 0.8$V (same orientations as Fig. 2).

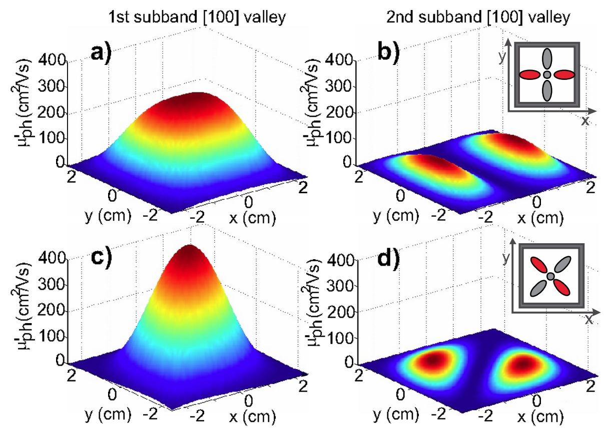

Fig. 4. Contribution to the SDM2 of the first two subbands of [100] valley. (a) and (b): (100)/[001] NWs. (c) and (d): (110)/[001] NWs.

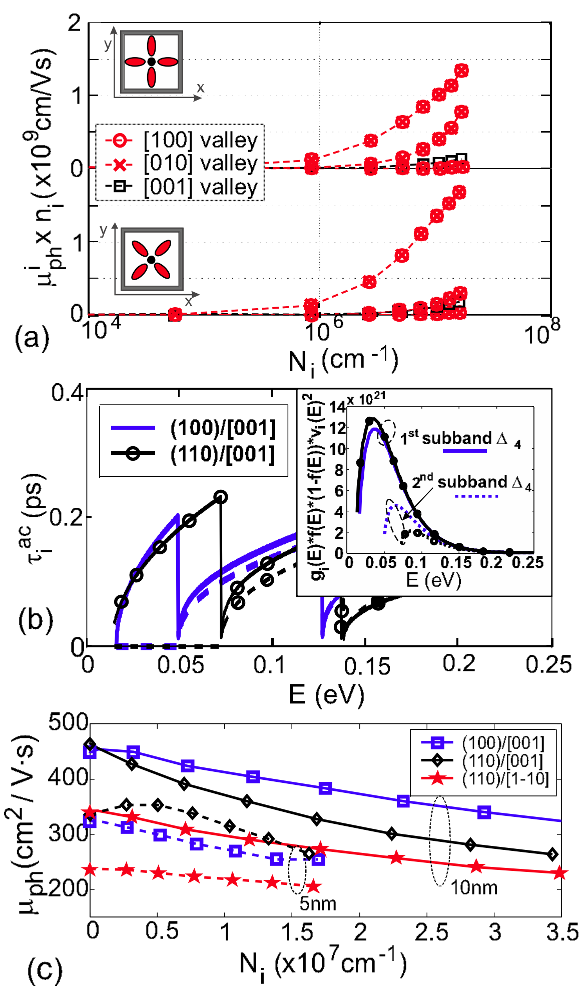

Fig. 5. (a) Contribution of i-th subband to μ_{ph} ($\mu_{ph}^i \times n_i$) for (100)/[001] and (110)/[001] NWs. (b) $\tau_i(E)$ and (in the inset) the rest of the parameters involved in Kubo-Greenwood formula, for (100)/[001] and (110)/[001] NWs. (c) μ_{ph} vs. N_i for different orientations (solid-lines for $W_{Si} = 10$nm, dashed-lines for $W_{Si} = 5$nm).