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Electroluminescence of Ge/SiGe p-MODFETs

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Abstract

In order to investigate impact ionization we have performed electrical DC measurements and electroluminescence (EL) spectroscopy on strained Ge on $Si_{0.4}Ge_{0.6}$ p-MODFETs. These measurements are discussed in comparison with energy band structure calculation and high electric field transport simulation. The energy band diagram is calculated using an original 30 band $k \cdot p$ Hamiltonian taking into account strain. The transport simulation based on a matrix resolution of the Boltzmann transport equation allows us to calculate impact ionization coefficients. The interpretation of EL results is based on hole energy subbands calculated in the confined Ge quantum well.

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Keywords: Electroluminescence; p-MODFET; Impact ionization; Full band energy structure; Strained Ge on SiGe

1. Introduction

A compressively strained Ge quantum well (QW) is the structure best suited to achieve high hole mobility due to the absence of impurity scattering with remote doping layers and to the low Ge hole effective mass. These features lead to very good low and high field transport properties for p-channel MODFETs and high potential for low-noise devices. Frequency records were reached with 0.1 μm Ge channel MODFETs with $f_{max} = 135$ GHz at 300 K and $f_{max} = 195$ GHz at 50 K [1]. A minimum noise figure $NF_{min} = 0.3$ dB (0.5 dB) with a noise resistance $R_n = 95\,\Omega$ and an associated gain $G_{ass} = 14$ dB (13 dB) were obtained at 1.2 GHz (2.5 GHz) in low power bias conditions ($V_{DS} = -0.75$ V, $I_{DS} = 4$ mA) corresponding to optimum extrinsic cut off frequency $f_T = 55$ GHz, intrinsic transconductance $g_{mmax} = 235$ mS/mm and output conductance $g_d = 7$ mS/mm. The characteristics show the potential of strained Ge channel p-MODFETs for low noise radiofrequency (RF) and microwave applications.

Impact ionization is known to reduce transistor lifetime strongly. In order to investigate impact ionization, we have performed electrical DC measurements and electroluminescence (EL) spectroscopy. In Section 2, we present the p-MODFET epilayer structure and the experimental setup. In the third section, the energy band structure and the transport properties of strained Ge are investigated to model impact ionization. Experimental results of electroluminescence (EL) are discussed in the last section.

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2. Epilayer structure and device technology

The epilayer structure of the Ge QW channel MODFET shown in Fig. 1 was grown by solid source molecular beam epitaxy (MBE) on a strain relieved SiGe buffer with a Ge content of 60%. The core of the active structure is a 9 nm thick strained Ge channel between two $Si_{0.4}Ge_{0.6}$ spacers, 5 and 3.5 nm thick and two 5 nm boron doped supply layers (doped at 8×10^{18} and $2\times10^{18}\,cm^{-3}$, respectively). The mushroom-shaped Ti/Au Schottky gate is patterned by e-beam technology. More details on the structure can be found in [2]. The investigated device has 0.1 μm gate length and 100 μm (2 × 50 μm) gate width.

The chip with several transistors is placed in an RF probe station designed for both electric (static, pulsed and microwave) and optical characterizations. Movable coplanar probes allow electrical contacts on the selected device. Fifty ohm matching is necessary to avoid RF oscillations of high HF performance transistors. The experimental setup for EL was described in [3]. The luminescence emitted from the electrically driven device is collected and focused onto the entrance slit of a 0.64 m monochromator and is detected with a liquid nitrogen cooled germanium detector. Lock-in and averaging techniques are used to obtain maximum sensibility for such low optical power measurement.

3. Band structure and transport properties of strained Ge

To investigate hot carrier phenomena like impact ionization in strained Ge, a direct matrix solution of the Boltzmann transport equation has been developed using a full band dispersion relation for bulk III–V and IV–IV semiconductors [4]. To obtain the strained Ge band diagram, the initial step is the band-structure calculation of bulk Ge using the $k\cdot p$ theory. For this purpose, we use an original thirty band $k\cdot p$ Hamiltonian H_{kp} taking into account the spin–orbit coupling. H_{kp} was shown to be valid up to 5 eV above and 6 eV under the top of the valence band all over the Brillouin zone for both direct and indirect band gap semiconductors [5]. The basis functions are the same Bloch functions as the ones used by Cardona and Pollak [6] to describe the Si and Ge band structures without spin–orbit coupling. We have introduced spin–orbit interaction because it cannot be neglected in Ge in which the spin–orbit splitting is more than 20% of the band gap energy.

Germanium is an indirect gap semiconductor. The absolute minimum of the conduction band (CB) is in the L valley as shown in Fig. 2. The probability of radiative recombination is thus a priori weak.

To solve the electronic Schrödinger equation in strained Ge on $Si_{1-x}Ge_x$ with a biaxial [0 0 1]-strain, we use the total Hamiltonian $H = H_{kp} + H_{st}$, where H_{st} is a strain Bir-Pikus Hamiltonian. The biaxial strain has two contributions on the Ge band structure: a hydrostatic stress, which causes a band gap energy shift, and a uniaxial stress which produces an additional splitting of the degenerate levels by lowering the lattice symmetry. H_{st} is connected to the deformation tensor using three hydrostatic and two uniaxial potentials [7].

Strain has strong consequences on band diagram particularly in the valence band, it lifts the degeneracy between heavy holes (HH) and light holes (LH) at the center of the Brillouin zone. The LH states are lowered as compared to the HH states, as shown on the right side of Fig. 3. In the conduction band, strain splits the four equivalent in-plane valleys Δ_4 and the two valleys along the growth direction Δ_2. All the L valleys remain equivalent.

This strained Ge band structure has been introduced in a direct matrix resolution of the Boltzmann transport

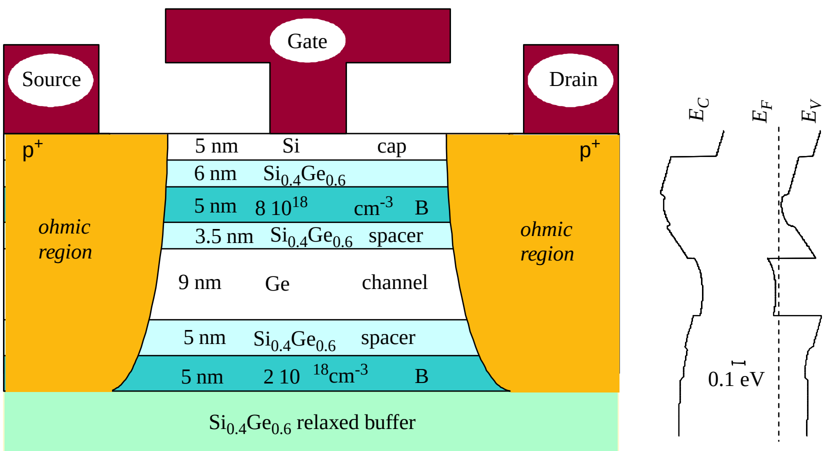

Fig. 1. p-MODFET layer structure and corresponding band diagram. The dot line represents the Fermi level.