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Terahertz emission from silicon nanostructures heavily doped with boron

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Abstract. We present the first findings of the terahertz emission from the ultra-narrow p-type silicon quantum well confined by the δ-barriers heavily doped with boron on the n-type Si (100) surface. The THz spectra revealed by the voltage applied along the Si-QW plane appear to result from the radiation of the dipole boron centers.

1. Introduction and background

The device has been prepared on the n-type Si (100) surface within frameworks of silicon planar technology. Making a mask and performing photolithography after preliminary oxidation, the short time diffusion of boron was used to obtain the ultra-shallow p+-n junctions [1]. The cyclotron resonance measurements as well as the infrared and local tunneling spectroscopy data have shown that the p+-boron diffusion profile represent the ultra-narrow p-type silicon quantum well (Si-QW), $2\,nm$, confined by the δ-barriers, $3\,nm$, heavily doped with boron on the n-type Si (100) surface (see figure 1). The SIMS and STM studies have shown that the δ-barriers heavily doped with boron in the concentration of $5 \cdot 10^{21}\,cm^{-3}$ represent really alternating arrays of silicon empty and doped dots, with dimensions restricted to $2\,nm$. This value of the boron concentration seems to indicate that each doped dot located between empty dots contains two impurity atoms of boron. The EPR studies show that these boron pairs are the trigonal dipole centers, which result from the negative-U reconstruction of the shallow boron acceptors, $2B(0) \Rightarrow B(+) + B(-)$. The electrical resistivity, magnetic susceptibility and specific heat measurements demonstrate that these dipole boron centers inside the δ-barriers appear to create the correlation energy gap which is regenerated in the superconductor energy gap, with the value of $0.044\,eV$ corresponding to the critical temperature and magnetic field equal to $T_c = 145\,K$ and $H_{c2} = 0.22\,T$ [1]. Besides, the correlation energy gap appears to cause the THz emission under the voltage applied along the Si-QW plane, with the frequency selected by varying the dimensions of the microcavities created between contacts (see figure 1).

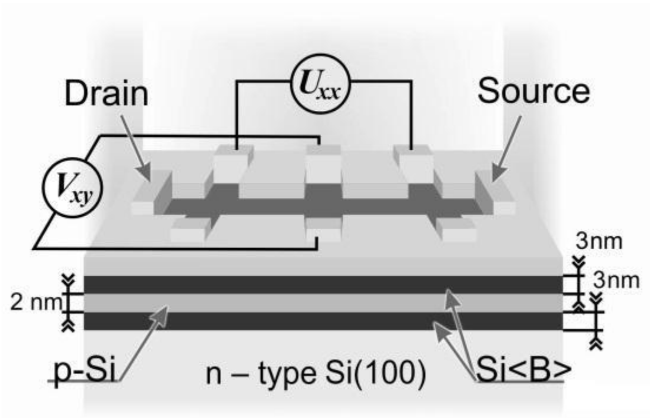

Figure 1. Device schematic, showing the perspective view of the silicon device structure performed within the frameworks of the Hall geometry. The silicon sandwich represents the p-type silicon quantum well confined by the δ-barriers heavily doped with boron on the n-type Si (100) surface. The source and drain Ohmic contacts are marked by S and D, respectively. The terahertz emission is caused by the drain-source current, Ids.

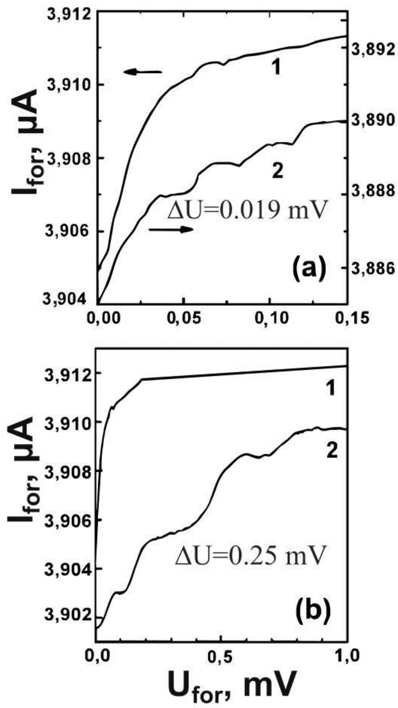

Figure 2. The Shapiro steps that reveal the THz frequency generation at $0.0093\,THz$ (a) and $0.129\,THz$ (b). The drain-source current was stabilised. $h\nu = 2e\Delta U$; ΔU denotes the step length [2]; curves 1 - $I_{ds} = 0$; curves 2 - $I_{ds} = 10\,nA$. $T = 77\,K$.

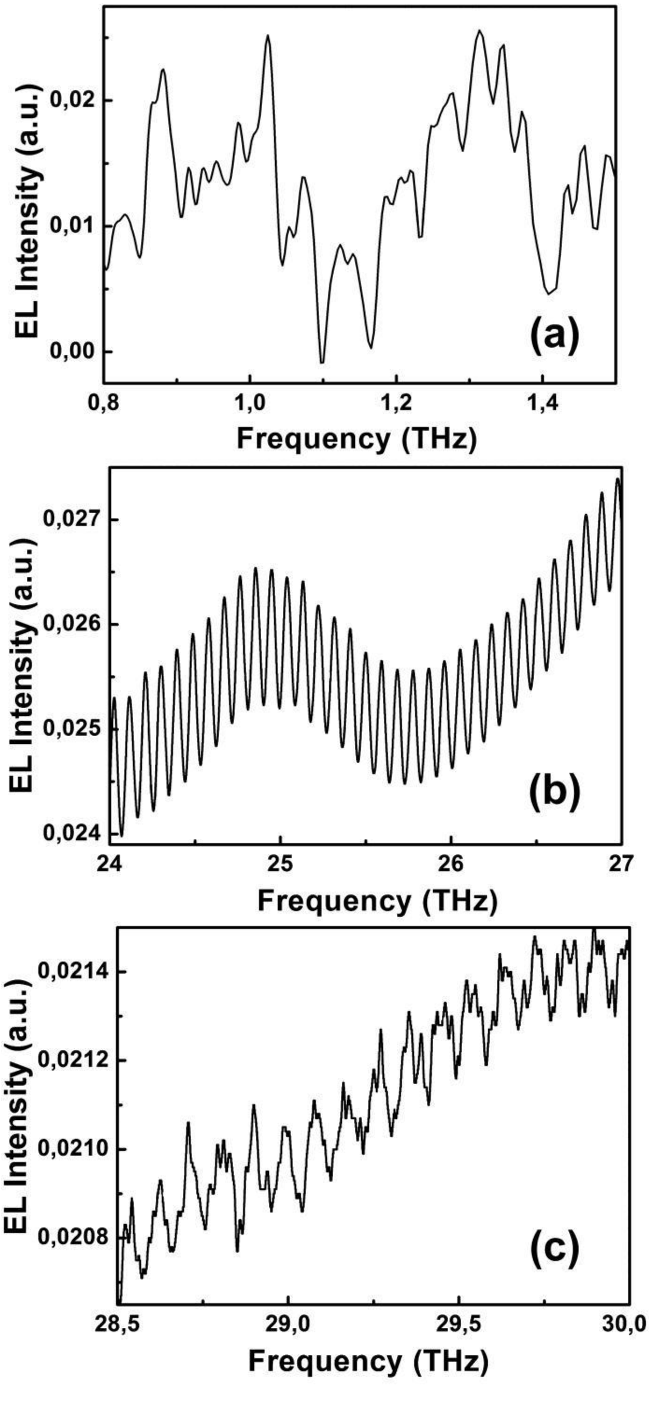

Figure 3. The THz modulated black body radiation that is induced by the stabilized drain-source current in different spectral range; $T=300\ K$; $I_{ds}=40\ mA$; The modulation frequency of 0.129 THz (a, b, c) and 0.0093 THz (a, c) due to the THz emission of the dipole boron centers are present.

2. Results

The THz and GHz emission caused by the radiation of the dipole boron centers was revealed by measuring the Shapiro and Fiske steps under the stabilized drain-source current that defined the values of the frequency, ν, as $0.0093\,THz$ and $0.129\,THz$ which are in a good agreement with the cross and longitudinal sizes, d, of the device, $d = c/2n\nu$; where n denotes refraction coefficient (figure 2a and 2b). The energy subbands of the two-dimensional holes in the Si-QW valence band have been also identified by the optical and electrical measurements.

This THz emission appears to be revealed as the modulation frequency of the black body radiation of the device that was measured with the Bruker-Physik VERTEX 70 FT-IR spectrometer (Figures 3a, b and c). These findings seem to be due to the oscillations of the heat capacity that are induced by the THz emission of the dipole boron centers inside the δ-barriers confining the Si-QW. Finally, by varying the Vxy applied voltage and the drain-source current, the phase shifts of the THz modulation appear to be observed as a result of the spin interference effects (figures 4a and b)

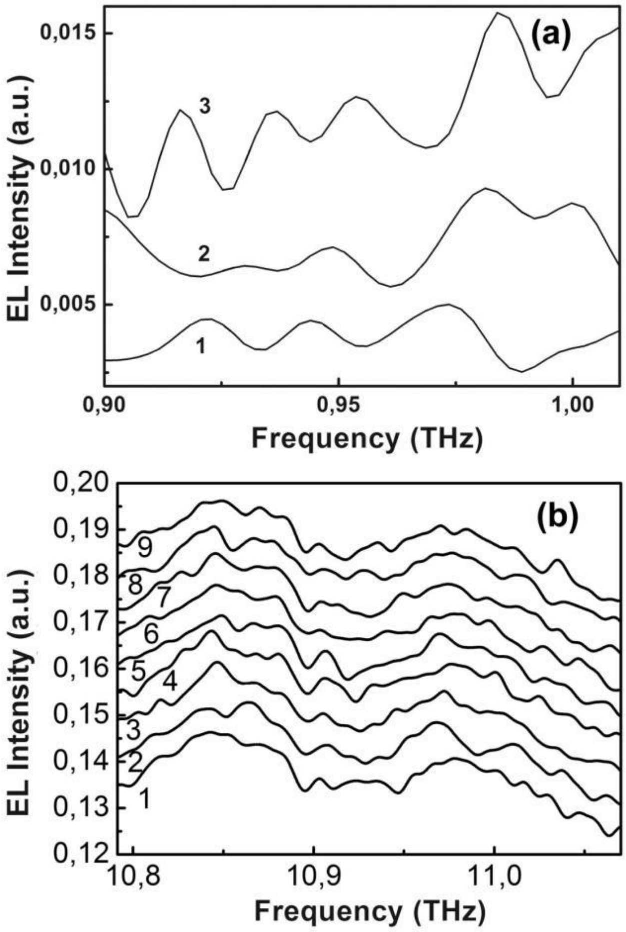

Figure 4. The phase shifts of the $0.129\,THz$ and $0.0093\,THz$ modulation spectra induced by varying the stabilized drain-source current (a) and by biasing the voltage applied to the Hall contacts; $T = 300\,K$; (a) $Ids = 30\,mA$ (1), $40\,mA$ (2), $80\,mA$ (3). (b) $Vxy\ (mV)$: 1 - -250; 2 - -150; 3 - -50; 4 – 0; 5 - $+50$; 6 - $+100$; 7 - $+150$; 8 - $+200$; 9 - $+250$.

References

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