Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 694-696 **PD-4-7**

Quantum-Well Silicon p-n Junctions and n-p-n Transistor Structures

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Abstract. Kick-out and dissociative vacancy diffusion mechanisms have been investigated by doping the monocrystalline silicon with boron and phosphorus. The criteria for dominance of each mechanism, established by varying the diffusion temperature and oxide overlayer thickness, were used to obtain the quantum-well p–n junctions and transistor structures featuring the high external quantum efficiencies over a broad spectral range. The reverse bias induces the power stimulated infrared emission from heavily doped QW p–n junctions because of the annihilation 2D excitonic correlations.

Non-equilibrium diffusion of boron and phosphorus has been performed in monocrystalline silicon using controlled surface injection of self-interstitials and vacancies. The diffusion temperature, the composition of the atmosphere during diffusion,and the thickness of the oxide overlayers on both working and backside of the wafer have been determined as the principal means of controlling the fluxes of excessive self-interstitials and vacancies responsible for the kick-out and dissociative vacancy diffusion mechanisms, respectively.[1)-3)] By varying the parameters of the surface oxide layer and diffusion temperature in the process of boron/ phosphorus diffusion, it was possible to define the conditions leading to the parity between these diffusion mechanisms, which corresponds to the suppression of imputity diffusion. The deceleration of the diffusion process thus achieved has permitted, for the first time, the fabrication of heavily doped quantum-well p–n junctions and n–p–n transistors with the diffusion profile depth that could be controlled over the 50–250 Å range (Figs. 1–4). The quantum-well silicon p–n junctions exhibited low dark leakage currents (fig. 2) and high external quantum efficiencies over a broad spectral range (fig. 5). Owing to the quantum-well type of the base, the Si n–p–n structures obtained can operate both as a bipolar and a field-effect transistor, which was found capable of multimode tunneling,including emitter–to–collector and base–to–collector processes (fig. 4). Of these, the second process has been established to be metastable–due to the 2D dimensionality of the base.[4)]

As a result of strong charge correlations that enhance Kohn screening singularities, a gap in the density of states of degenerate hole gas has been found using the I–V characteristics.[5)] These data are evidence of the 2D excitonic insulator formation in the Si heavily doped quantum-well p–n and n–p–n structures ($N(B)$; $N(P)>10^{20}$ cm). The annihilation of 2D excitonic correlations has been found to induce the power infrared emission under both the direct/reverse voltage and the voltage heating carriers along p–n junction area[6)] (fig. 6).The threshold character of the irradiative power as a function of the reverse current demonstrates the first observation of stimulated light emission from silicon planar structures (fig. 7).

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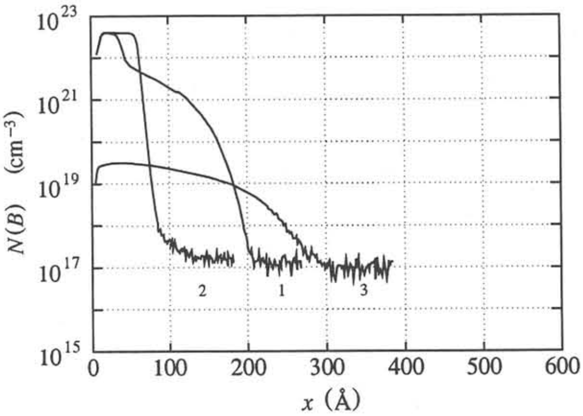

Figure 1. Quantum-well diffusion profiles obtained for boron dopant in n–type silicon wafers with the thin oxide overlayer at diffusion temperatures of:
1 — 800°C (dissociative vacancy diffusion mechanism),
2 — 900°C (the parity between different diffusion mechanisms),
3 — 1100°C (kick-out mechanism).

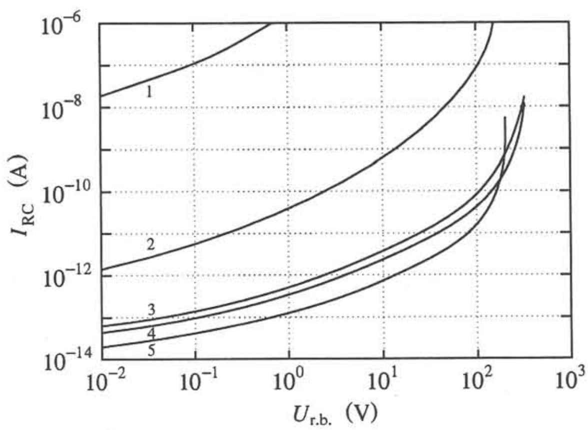

Figure 2. Reversal current–voltage characteristics of quantum-well p–n junctions obtained in n–type silicon wafers with thin (1,2) and thick (3,4,5) oxide overlayer at diffusion temperature of 850°C.

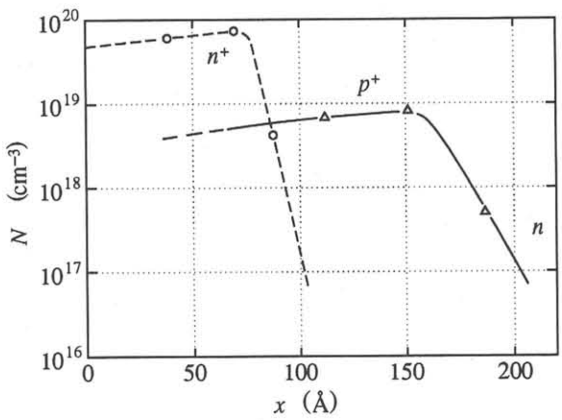

Figure 3. Quantum-well n^+–p^+–n structure obtained in the n–type silicon wafer with thick oxide overlayer by successive boron/phosphorus diffusion at 900°C

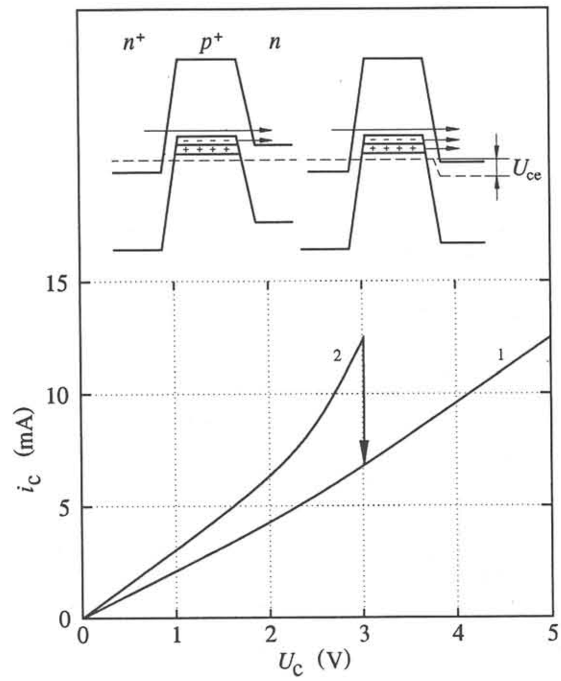

Figure 4. Direct collector current–voltage characteristics of bipolar quantum-well n^+–p^+–n transistor structure obtained in n–type silicon wafer using successive boron/phosphorus diffusion at 900°C.
1 – emitter–to–collector tunneling process
2 – base–to–collector tunneling process

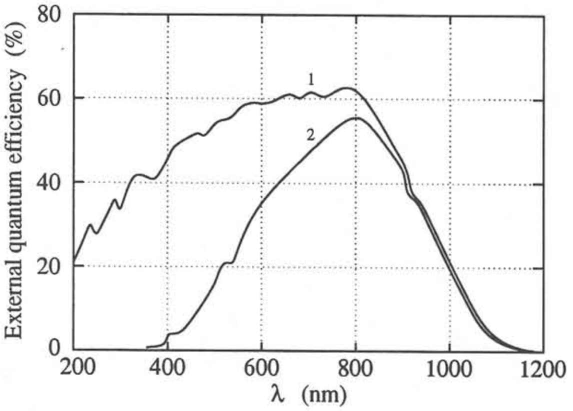

Figure 5. External efficiency quantum spectra measured on right(1) and backside (2) of the n–type silicon wafers with the quantum-well p–n junction obtained at 900°C and medium oxide overlayer.

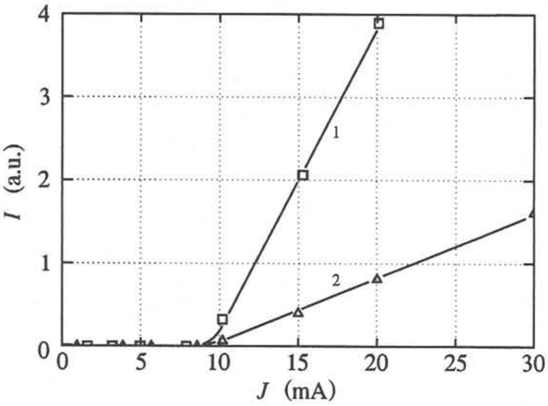

Figure 7. The power of the infrared emission as a function of the reverse current for the quantum-well silicon p–n junction with the depth corresponding to the curve 2 in fig.1 1 — λ=5.25 μm, 2 — λ=3 μm.

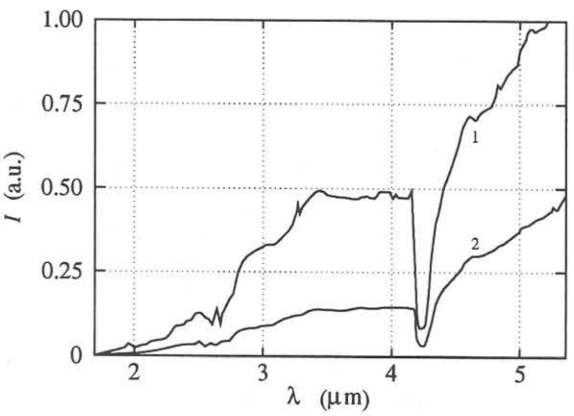

Figure 6. Spectra of infrared emission at 300 K under reverse voltage applied to the quantum-well silicon p–n junctions with the depth corresponding to the first (curve 2) and second (curve1) QW diffusion profiles shown in fig.1. 1 — 1600 mW/mm (50mA); 2 — 680 mW/mm (50 mA).