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The growth of ultra-uniform B-doped Si/SiGe multiple quantum wells by RTCVD for mid-IR applications

W Zheng[1], J C Sturm[1], C F Gmachl[1], T Buyuklimanli[2], J Marino[2], M S Denker[2] and J T Mayer[2]

[1] Department of Electrical Engineering, Princeton Institute for the Science and Technology of Materials, Princeton University, Princeton, NJ 08544, USA
[2] Evans Analytical Group, 104 Windsor Center, Suite 101, East Windsor, NJ 08520, USA

E-mail: wzheng@princeton.edu

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Abstract
A process for the growth of uniform boron-doped Si/SiGe multiple quantum wells by rapid thermal chemical vapour deposition for studying intersubband transitions for quantum cascade laser applications has been developed. The doping density profiles are extremely sharp (∼2 nm/decade and ∼3 nm/decade for the leading and trailing boron edges, respectively) measured by high resolution secondary ion mass spectroscopy, and the well-to-well uniformity is excellent. A higher temperature is used for the silicon layers (625 °C) compared to the SiGe layers (525 °C) to keep the growth rate of both layers in the range of 0.1 nm s^{-1}.

1. Introduction

The quantum cascade (QC) approach for infrared light emission relies only on intersubband transitions and not on a direct band gap. Applied to the Si/SiGe material system, it offers an opportunity to develop electrically pumped Si-based light emitters and lasers [1–4]. At the heart of a typical QC structure is a series of doped quantum wells (QWs) in which optical transitions take place. Because the process depends on intersubband levels, sharp and planar interfaces and abrupt doping are more critical for QCLs compared to conventional devices, such as HBTs. Furthermore, achieving gain with a narrow linewidth demands extreme repeatability of the QW width and composition. Growth of Si/SiGe multiple quantum wells (MQWs) by both MBE and CVD, characterized by secondary ion mass spectroscopy (SIMS), has been reported by several groups [5–7], but the well-to-well uniformity and surface planarity have not been studied in detail. Here, we report the growth of boron-doped Si/SiGe MQW structures by rapid thermal chemical vapour deposition (RTCVD) optimized for interface abruptness, surface planarity, background doping and well-to-well uniformity.

2. Experimental procedure

The structures were grown by RTCVD with *in situ* measurement of infrared transmission to measure temperature (figure 1) [8]. The wafers used for the experiments were 100 mm diameter boron-doped double-side-polished Si (1 0 0) wafers with a resistivity of ∼10–20 Ω cm. The wafers were chemically cleaned using H_2SO_4:H_2O_2 (30%) 1.5:1 for 15 min and followed by a dilute HF dip before loading into the chamber.

Low background doping is critical in QCLs to achieve a uniform electrical field, but due to the history of our reactor, RTCVD of SiGe with dichlorosilane as a silicon source (our usual choice) had high background phosphorous levels on the order of 10^{17} cm^{-3}. Figure 2 shows the background phosphorous levels as a function of germanium concentration for both dichlorosilane and silane silicon sources. Silane-based growth had acceptable phosphorous levels (∼10^{16} cm^{-3}) compared to dichlorosilane-based growth and was used for the rest of the work in this paper.

We now focus on the growth of boron-doped Si/SiGe multiple quantum wells with 15 periods to study hole intersubband transitions and infrared absorption and emission. Figure 3 shows the growth rate and Ge concentration as a

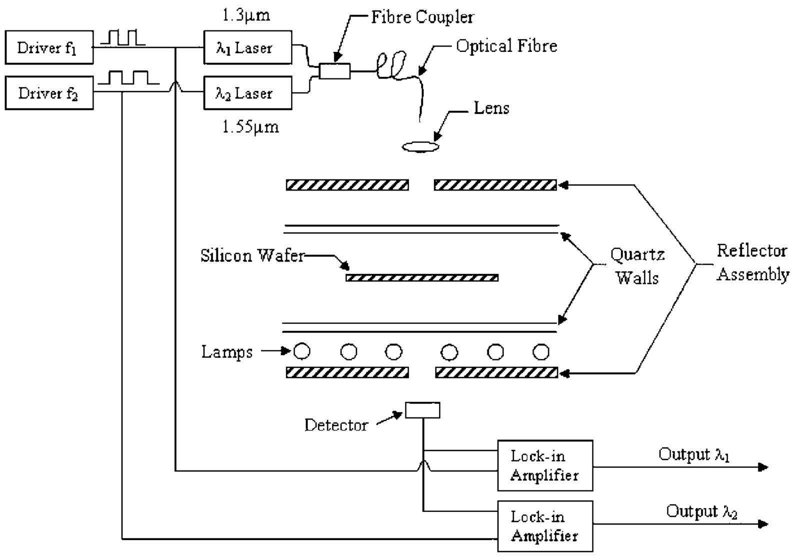

Figure 1. Schematic diagram of the rapid thermal processing system adapted for infrared transmission measurements [8].

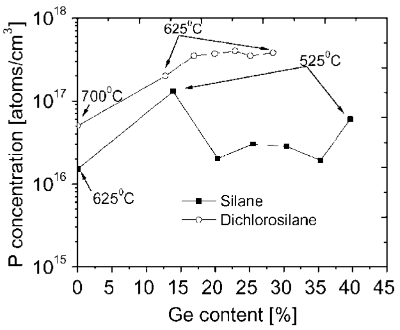

Figure 2. N-type background doping for both silane and dichlorosilane silicon sources as a function of germanium content; the growth temperatures ranged from 525 °C to 700 °C, with a growth pressure of 6 Torr and a hydrogen carrier of 3 slpm. The silane flow was 10 sccm and the dichlorosilane flow was 6.5 sccm.

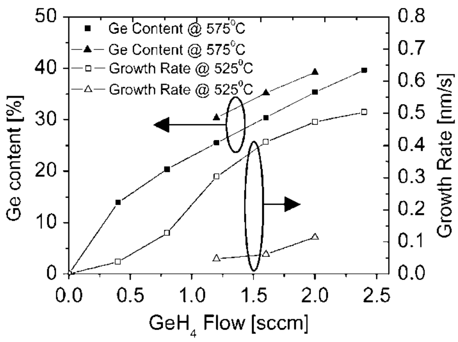

Figure 3. Growth rate and Ge concentration versus germane flow rate using silane as a precursor at 525 °C and 575 °C. The pressure is 6 Torr with a 3 slpm hydrogen carrier, and the silane flow is 10 sccm.

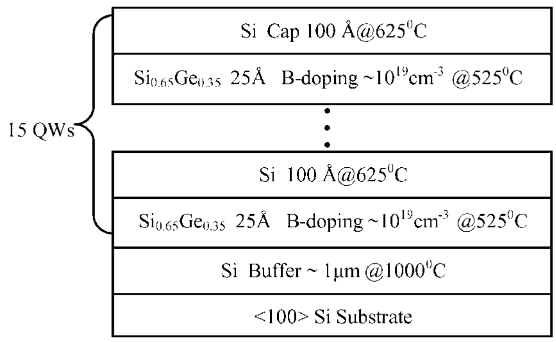

Figure 4. Cross section of the targeted sample structure.

function of germane flow for conditions of 575 °C and 525 °C, respectively, with a growth pressure of 6 Torr, using a hydrogen carrier flow of 3 slpm and a silane flow of 10 sccm. As the germane flow is increased, both the Ge concentration and the growth rate increase. To achieve a sharp interface, we seek a low growth rate, on the order of ∼0.1 nm s^{-1}. This is because of finite time to switch gases between layers and because a low growth rate is associated with a more planar interface [9]. Due to the higher growth rate of SiGe compared to Si, a temperature lower than 625 °C which is used for the growth of Si is needed. The growth rate of SiGe at 575 °C for 35% Ge (target for our work) is ∼0.5 nm s^{-1} which is too high. Therefore, we decreased the temperature to 525 °C and achieved a growth rate of ∼0.06 nm s^{-1} for 35% Ge.

For growth, an undoped Si 1 μm buffer layer is first grown on the Si substrate. The multiple quantum well structure consists of 15 periods, each with a target of 2.5 nm thick $Si_{0.65}Ge_{0.35}$ well and 10 nm thick Si barrier (figure 4). The quantum wells are doped p-type with diborane varying from $\sim 2 \times 10^{18}$ cm^{-3} to $\sim 3 \times 10^{19}$ cm^{-3} in different samples. Within a single quantum well, the $Si_{0.65}Ge_{0.35}$ layer thickness of 2.5 nm compares to an equilibrium critical thickness of ∼40 nm for a single such layer on Si(1 0 0). The average composition of the entire MQW structure of 2.5 nm thick SiGe with 35% Ge is 7%, with a thickness of ∼200 nm. This compares to an equilibrium critical thickness of ∼3 μm for a single layer of 7% Ge [10].

3. Results and discussion

The surface roughness of the samples measured by AFM after the entire 15 QWs was less than 0.5 nm, showing good interface planarity, enabled by the low growth rate.

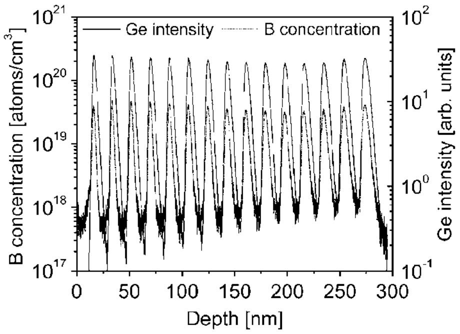

Figure 5. SIMS profiles of Ge and B of the MQWs sample.

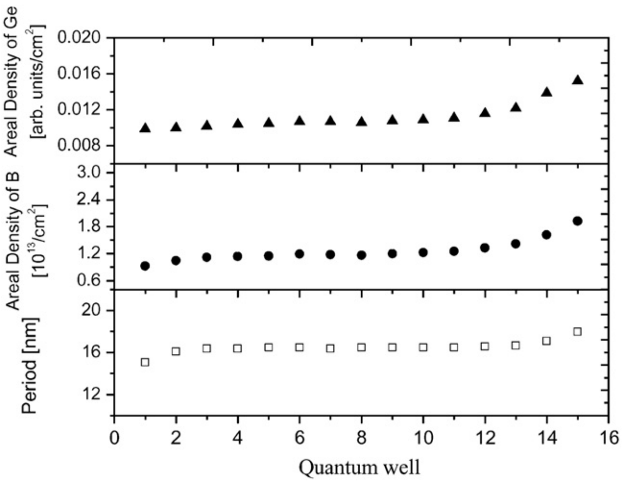

Figure 6. The period and areal densities of B and Ge for each quantum well.

High resolution SIMS measurements with an oxygen primary beam were performed (figure 5). The oxygen primary ion bombardment was used at low energy less than 2 keV. The SIMS profiles were collected with a PHI mass spectrometer using a quadrupole mass detector. The doping density profiles are extremely sharp (∼2 nm/decade and ∼3 nm/decade for the leading and trailing boron edges, respectively), with ∼3 nm FWHM. These compare favourably to profiles of a similar structure grown by UHV-CVD of ∼3 nm/decade and ∼6.5 nm/decade for the leading and trailing boron edges, respectively [7], although the results in all cases are affected by SIMS broadening effects.

As a quantitative test of well-to-well uniformity, figure 6 shows the period and the integrated areal density of boron and germanium in each quantum well. The middle 11 QWs show a nearly identical period of 18.2 nm with standard deviation about 0.1 nm (less than 1% of the period length). To the best of our knowledge, this reports one of the most uniform Si/SiGe MQWs reported to date. The growth interruption when switching between SiGe and Si was 30 s. To grow the entire MQW structure requires ∼90 min. The uniformity implies that the temperature varied less than 1 °C over the ∼90 min of growth. The uniformity of the integrated B and Ge levels per well was also excellent.

The drop in the period and integrated densities near the surface is thought to be a SIMS artefact. The rise of the FWHM of boron and germanium near the bottom of the QWs is an effect consistently observed in several samples. Whether this is a SIMS artefact or real effect is not clear.

4. Conclusion

We have reported p-type Si/SiGe multiple quantum wells for intersubband transitions, grown by rapid thermal chemical vapour deposition with excellent well-to-well uniformity, as measured through high resolution secondary ion mass spectroscopy. Critical factors include the use of a silane source for low background doping, the growth of the SiGe layer at a lower temperature to achieve a low growth rate and repeatable temperature control.

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