Growth of Ultra-uniform B-doped Si/SiGe Multiple Quantum Wells by RTCVD for Mid-IR Applications

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1. Introduction

The quantum cascade (QC) approach for infrared light emission relies only on intersubband transitions and not 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 in which the optical transitions take place. Sharp and planar interfaces and abrupt doping are more critical for QCLs compared to conventional devices, such 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 SIMS, have been reported by several groups [5, 6], but the well to well uniformity has not been studied in detail. Here, we report the growth of B-doped Si/SiGe MQW structures by rapid thermal chemical vapor deposition (RTCVD) for intersubband transitions with extreme uniformity and interface abruptness.

2. Results and Discussion

The structures were grown by RTCVD with *in situ* measurement of infrared transmission which enables rapid temperature switching (Fig. 1) [7]. Low spurious background doping is critical in QCLs to achieve a uniform field, but due to reactor history, RTCVD of SiGe with dichlorosilane as a silicon source had high background phosphorous levels. Silane-based growth had acceptable (10 times lower) phosphorous levels, and the growth temperature was lowered to 525^0C for SiGe to achieve growth rates ~1Å/s (Figs. 2, 3). Our work focused on boron-doped Si/SiGe superlattices (Fig. 4) with 15 periods for hole intersubband transitions. SiGe was grown at 525^0C (~35% Ge, ~0.6 Å/s) and silicon at 625^0C (~0.3 Å/s) with pressure controlled at 6 torr and a hydrogen carrier.

The surface roughness measured by AFM after the entire 15 QWs was less than 0.5nm, showing good interface planarity, enabled by the low growth rate. High resolution SIMS measurements with an oxygen primary beam were performed (Fig. 5). Although the doping density profiles are extremely sharp (~ 2nm/decade and ~ 3nm/decade for the leading and trailing boron edges, respectively, and ~ 3nm FWHM), the exact well profile can not be resolved. As a quantitative test of uniformity, Fig. 6 shows the period and the integrated area 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 the most uniform Si/SiGe MQWs reported to date. This implies the temperature varied less than 1^0C over the ~90 minutes of growth. The uniformity of the integrated B and Ge levels per well was also excellent. The period and integrated densities dropped near the surface and rose near the bottom of the QWs, an effect consistently obtained in many similar samples. Whether this is a SIMS artifact or a real effect is under investigation by varying the SIMS conditions.

3. Conclusion

We have reported p-type Si/SiGe MQWs for intersubband transitions, grown by RTCVD with excellent well to well uniformity, as measured through high resolution SIMS.

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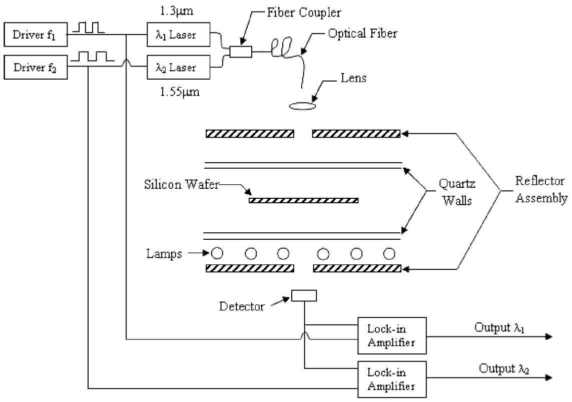

Fig. 1. Schematic diagram of the rapid thermal processing system adapted for infrared transmission measurements

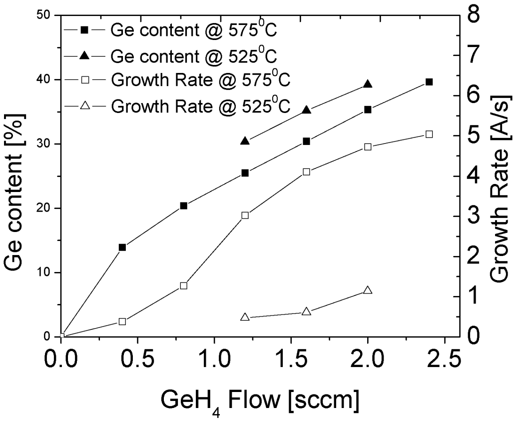

Fig. 3. Growth rate and Ge concentration versus germane flow rate using silane as a precursor at 525^{0}C and 575^{0}C. Pressure is 6 torr.

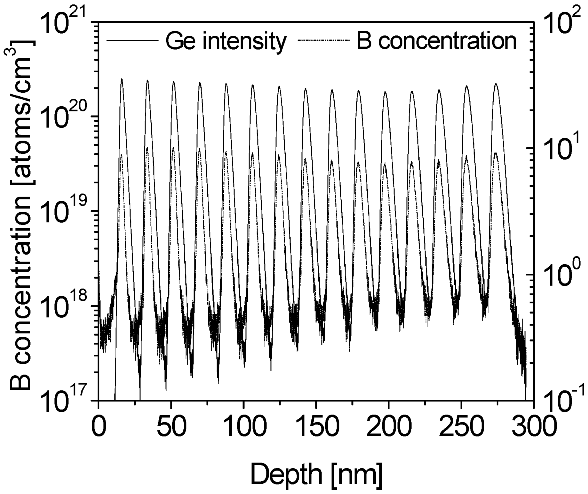

Fig. 5. SIMS profiles of Ge and B of the MQWs sample

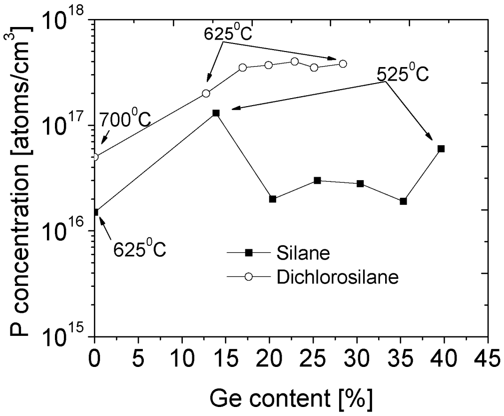

Fig. 2. N-type background doping for both silane and dichlorosilane silicon sources as a function of germanium content, the growth temperatures ranged from 525^{0}C to 700^{0}C, with growth pressure of 6 torr and a hydrogen carrier

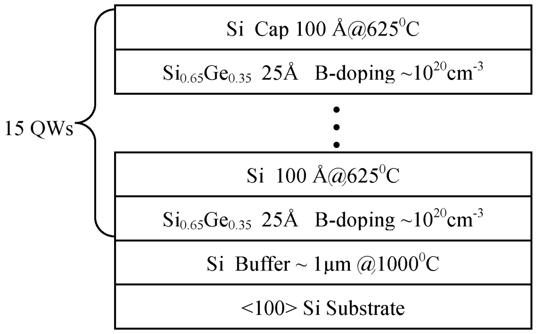

Fig. 4. Cross section of the sample structure

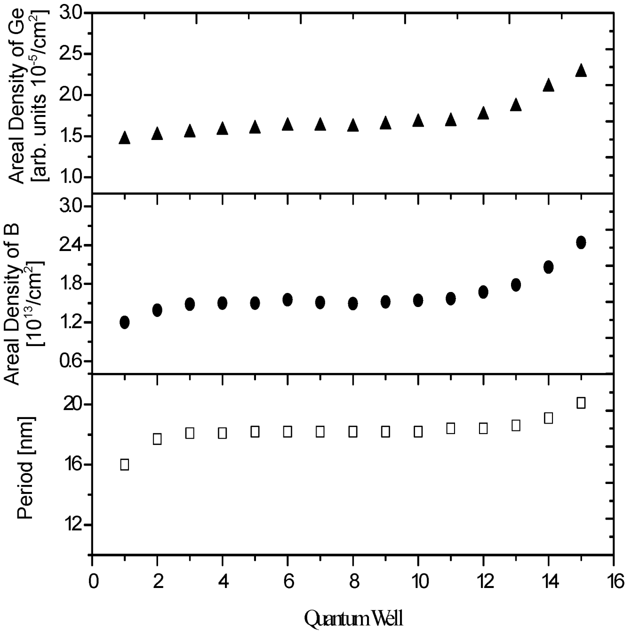

Fig. 6. The period and area densities of B and Ge for each quantum well.