Excimer Laser-Assisted In Situ Phosphorus Doped $Si_{(1-x)}Ge_x$ Epilayer Activation

Jicheul Bae and Youngjae Lee

This paper presents results from experiments on laser-annealed SiGe-selective epitaxial growth (LA-SiGe-SEG). The SiGe-SEG technology is attractive for devices that require a low band gap and high mobility. However, it is difficult to make such devices because the SiGe and the highly doped region in the SiGe layer limit the thermal budget. This results in leakage and transient enhanced diffusion. To solve these problems, we grew in situ doped SiGe SEG film and annealed it on an XMR5121 high power XeCl excimer laser system. We successfully demonstrated this LA-SiGe-SEG technique with highly doped Ge and an ultra shallow junction on p-type Si (100). Analyzing the doping profiles of phosphorus, Ge compositions, surface morphology, and electric characteristics, we confirmed that the LA-SiGe-SEG technology is suitable for fabricating high-speed, low-power devices.

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I. Introduction

For ultra large-scale integration, the Si-based metal-oxide-semiconductor field-effect transistor (MOSFET) is the ideal candidate, and the MOSFET technology is well developed for this purpose. Nowadays, reliable devices feature sizes of 50 nm, and it is possible to achieve a package density of more than 30 million transistors on a processor chip and a clock frequency of more than 2 GHz [1]-[3]. On the other hand, the intrinsic physical properties of the MOS system limit the performance of the devices. The amorphous Si/SiO_2 interface degrades the charge carrier mobilities, and the complementary MOS (CMOS) circuits use very low hole mobilities. In order to increase the high-frequency performance of transistors, many researchers have investigated new materials, such as SiGe/C heterostructures [4]. They provide superior transport properties and the well-developed Si technology goes well in combination with the SiGe heterostructure [4], [5].

An SiGe selective epitaxial growth (SEG) technique is needed for the 21st sub-50 nm CMOS technology [1]. For example, atomic layer doping, elevated source/drain formation, and strained/unstrained SiGe layer technologies have been introduced [1]-[3], [6]. However, it is very difficult to make high speed, ultra-low power devices, because the conventional annealing temperature necessary to activate dopants is below 800 °C, and this thermal budget cannot be tolerated in Si/SiGe layer samples [7]. To overcome the obstacles and get a good quality doped SiGe SEG layer with abrupt doping profiles and transport properties, we present a new excimer laser-annealed (LA) SiGe SEG technology.

II. Experiment

Figure 1 gives the process flow for the SiGe selective

epitaxial growth with laser and spike rapidly thermal annealing (RTA), starting with an LA-SiGe SEG layer on p-type Si (100). The samples were first subjected to an RCA cleaning followed by a 99:1 H_2O/HF dip for 1 minute.

We placed the pre-cleaned samples coaxially into a silicon carrier and loaded them into the load-lock chamber. The pressure of the load-lock chamber reached a base pressure below 10^{-6} torr. When this pressure was reached, the samples were loaded into the main chamber together with flowing nitrogen. The growth chamber was pumped down to a base pressure below 10^{-10} torr. Before the hydrogen atoms evaporated from the cleaned surface of the samples, the source gases were fed into the main chamber. The samples were treated for a minimum of 5 minutes at 800 °C to remove interfacial oxide of approximately 13 Angstroms.

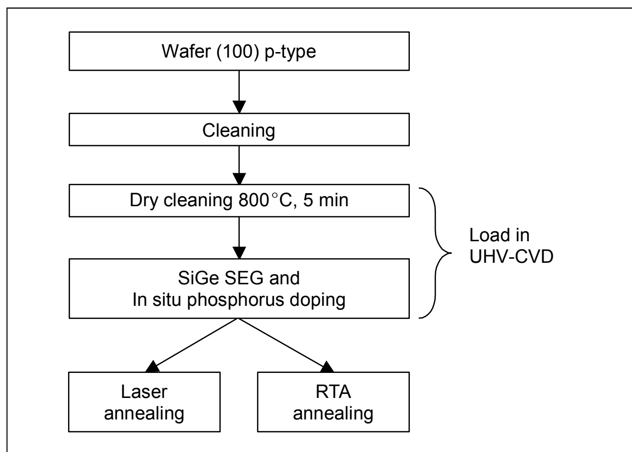

Fig. 1. Process sequence of SiGe selective epitaxial growth with laser and spike RTA annealing.

Typical source gases used for this system were Si_2H_6 and GeH_4 for the Si and SiGe epilayers. The dopant gas was PH_3 for n-type. We maintained the operating growth pressure at 10^{-4} torr and applied an ultra-high vacuum chemical deposition system to the in situ doped SiGe SEG.

An excimer laser annealing and spike RTA process followed the SiGe SEG step to activate the epilayer. The normal annealing used the spike RTA at 1050 °C for 5 seconds. The excimer laser annealing was carried out on an XMR5121 high-power XeCl excimer laser (λ=308 nm) system operating in pulse mode with energy around 500 mJ/pulse, a pulse time of 60 ns (full-width half-maximum), and a repetition frequency of 30 Hz. The maximum spot size was 10$\times$10 mm^2 and could be adjusted to obtain the desired energy density. Due to the beam homogenizer, the uniformity of the beam intensity was about 10% within a 10$\times$10 mm^2 beam area. The sample was in a vacuum chamber at 10^{-7} torr and room temperature. The laser annealings were performed at 450, 530, and 700 mJ/cm^2.

III. In Situ Phosphorus Doped SiGe Selective Epitaxial Growth

Many researchers have investigated how to achieve a good quality SiGe epilayer, [5], [7]. As a result, the factors controlling the SiGe lattice are well known: growth temperature, layer thickness, and Ge composition [7]. To optimize the SiGe growth rate, we used a low temperature in the 550 to 680 °C range. Since these temperatures for SiGe processing are in the surface controlled range, temperature control determines both the SiGe thickness and the Ge composition. Therefore, the episystem has to provide an exact platform for the SiGe growth process with excellent temperature control and very low base vacuum. The UHV-CVD system has been demonstrated to successfully grow SiGe layers. In this system, the in situ doped SiGe SEG follows complicated processing steps using Si_2H_6, PH_3 and GeH_4 gases.

Using this system, Arrhenius plots of the SiGe epitaxial and in situ phosphorus doped SiGe growth rate as a function of the reciprocal temperature are achieved as shown in Fig. 2.

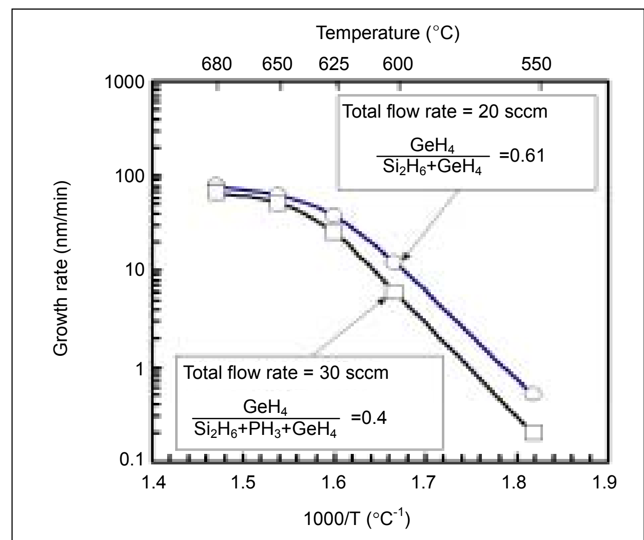

Fig. 2. Growth rate of SiGe film and in situ phosphorus doped SiGe film as a function of reciprocal temperature.

At a low temperature of 550 to 625 °C, the growth rate followed an exponential law. At higher temperatures of 625 to 680 °C, the growth rate tended to become temperature insensitive. In addition, the in situ doped SiGe growth rate using multigases is decreased by the process pressure and interference of dopants.

After the samples were grown, we used the X-ray diffraction method to analyze the Ge composition and lattice strain. Figure 3 shows the X-ray rocking curves with various Ge compositions in the $Si_{(1-x)}Ge_x$ epitaxial samples.

$$x = (a_{SiGe} - a_{Si})/(a_{Ge} - a_{Si}). \quad (1)$$

These Ge compositions were calculated by Vegard's law as shown in (1). When the Ge composition was 16%, the broad peak of the rocking curve in the boundary region indicated crystalline degradation in these areas. On the other hand, the rocking curves became sharp peaks at the lower Ge composition. In addition, the peak positions of the rocking curves in the SiGe/Si area shifted to the lower angle side and those in the Si area shifted to the higher angle side. This indicates that the Si area near the boundary had a decreased lattice constant, while the SiGe/Si area had an increased constant. However, when the Ge composition increased, the surface roughness enlarged, because the lattice mismatch and thermal stress distributed the high Ge composition epilayer.

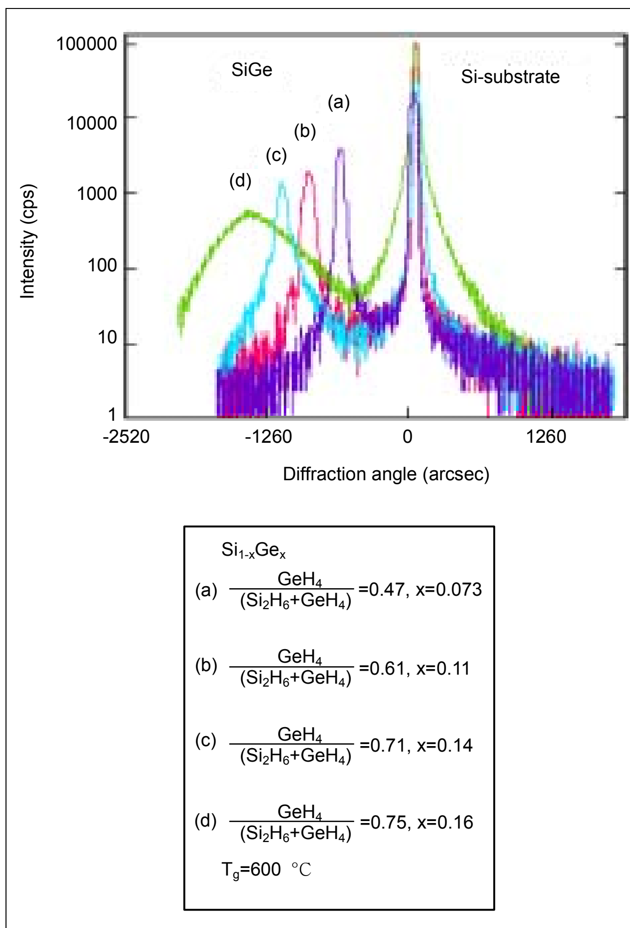

Fig. 3. X-ray rocking curves of SiGe epilayer for various Ge compositions. According to increase of Ge composition, peak positions of rocking curves in the Ge area are shifted to the lower angle side.

Figure 4 shows that the surface roughness of the SiGe film depended on temperature. At a lower temperature, the roughness

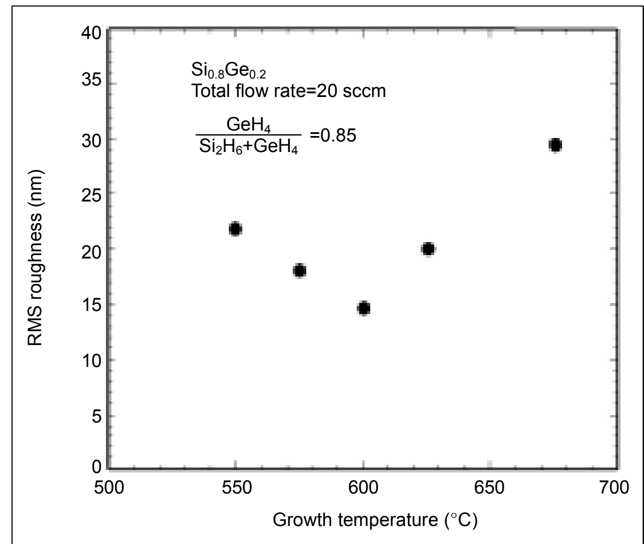

Fig. 4. Surface roughness of SiGe film as a function of temperature.

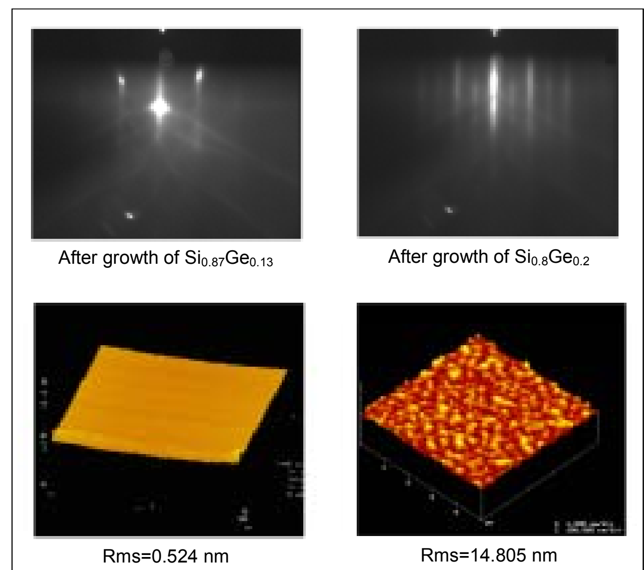

Fig. 5. Surface morphology and RHEED pattern of SiGe films thicker than 90 nm.

on the SiGe was increased by the distribution of crystalline degradation. At a higher temperature, the roughness on the SiGe was seriously increased by the thermal stress.

The top view of the SiGe epilayer and RHEED patterns using the AFM and RHEED instrument are shown in Fig. 5. When the Ge composition was 13%, the in situ RHEED pattern of the SiGe surface along (110) axes occurred and the illuminated spots were clearly bright. On the other hand, when the Ge composition was 20%, an unsteady SiGe epilayer was exhibited, because a rough crystalline surface produced a pattern consisting of numerous distinct spots arranged in a

regular pattern. Moreover, the higher Ge composition limited the epilayer thickness. While the epilayer thickness increased, a crosshatch pattern occurred along two (110) directions as shown in Fig. 6.

The typical crosshatch pattern connected with extended misfit dislocations within the graded part of the buffer is clearly visible. From the above experiments, we achieved a good quality in situ doped SiGe layer, which had a customized Ge composition, surface roughness, and lattice strain. Thus, in situ doped SEG with high Ge composition was successfully performed as shown in Fig. 7. For this experiment, each process was governed by and demanded accuracy of temperature and a very low process vacuum condition for the in situ doped $Si_{(1-x)}Ge_x$ SEG. Hence, to decrease the adsorption coefficient of the sources, an isolation process, which is called the local oxidation of silicon (LOCOS), was performed in the field region of the samples.

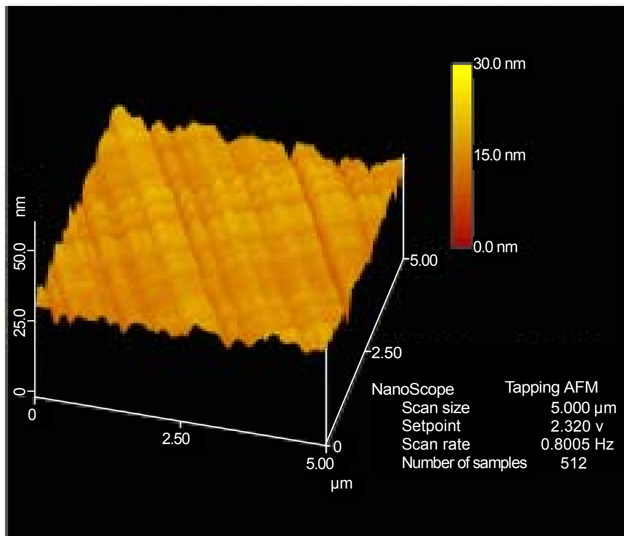

Fig. 6. Surface morphology of the thicker SiGe epilayer. A crosshatch pattern occurs along two (110) directions.

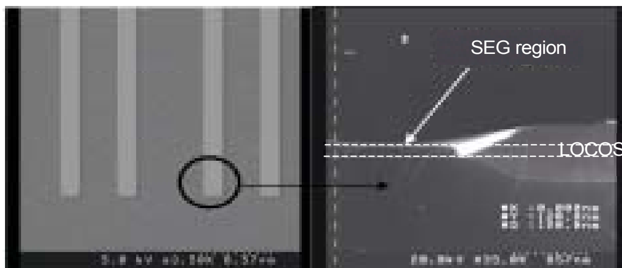

Fig. 7. SEM micrograph showing in situ phosphorus doped SiGe selective epitaxial growth. The SiGe SEG is performed at a high-pressure process condition using the UHV-CVD system, after LOCOS isolation process was performed.

IV. Excimer-Laser Annealed SiGe SEG Technology

For the in situ doped SiGe epilayer, the annealing required to activate the dopants is a very critical step. Therefore, the upper limit of allowed annealing temperatures was about 650 to 800 °C [7]. Furthermore, normal annealing problems, such as lowered electrical activation efficiency of implanted impurities, channeling, transient enhanced diffusion, poor recovery of damages, and so on, become more serious in the in situ doped SiGe epilayer [2], [3].

The solution is to use an excimer laser to locally heat and recrystallize the top film in the multiplayer stack [1]-[3], [7], [9]. This is due to the combination of the strong optical absorption of the UV light. The small heat diffusion length during the laser pulse (about 20 nm) implies that high temperatures can be developed only at the deposited Si-surface region, causing melting of Si, without appreciable heating (<400 °C) of the substrate. In order to investigate the influence of the laser-annealing energy on the sheet resistances, Ge composition, and doping profiles, we prepared several in situ doped SiGe samples.

We examined the depth and doping profiles using secondary ion mass spectrometry (SIMS). The SIMS doping profiles for Ge and P before and after spike RTA and excimer laser annealing (ELA) for in situ P-doped $Si_{0.86}Ge_{0.14}$ thin films are shown in Figs. 8 and 9. After using spike RTA at 1050 °C for 5 sec, the Ge profile showed only a little intermixing, but P diffused easier than Ge. After ELA with 450 and 700 mJ/cm^2, diffusion of Ge was abrupt, but P was more diffused than Ge. These results show that the diffusion depth of the the shallower junction was controlled by ELA. In addition, the impurity curve after spike RTA showed a serious transient enhanced

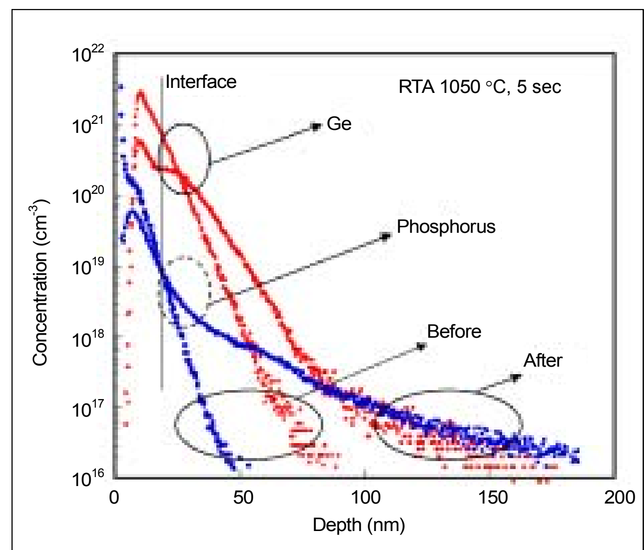

Fig. 8. SIMS doping profiles for Ge and phosphorus before and after spike RTA at 1050 °C for 5 seconds.

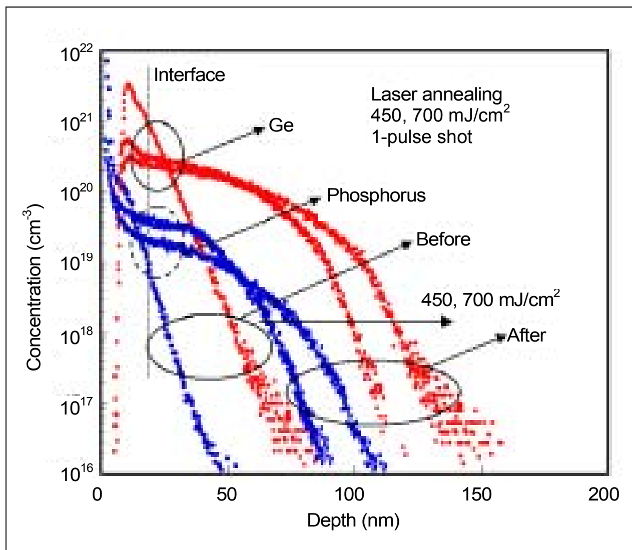

Fig. 9. SIMS doping profiles for Ge and phosphorus before and after excimer laser annealing at 450 and 700 mJ/cm^2, respectively.

diffusion in the low doping concentration region. The anomalous diffusion of dopants, known as transient-enhanced diffusion (TED), may severely increase the leakage currents. To suppress the TED, excimer laser annealing was performed by a XeCl excimer laser (λ=308 nm) system and explored as a function of energy density. The ELA results reveal an abrupt Ge and phosphorus doping profile. Figure 10 shows that the sheet resistance was significantly reduced. When the Ge composition was 14% with RTA and laser annealing, the sheet resistance was 45 and 36Ω/sq, respectively, and when the Ge composition was 0%, the sheet resistance was 230 and 150Ω/sq as an initial p-type Si condition.

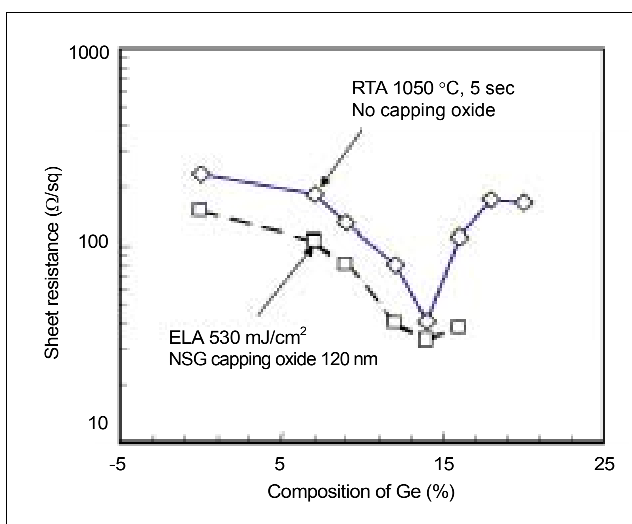

Fig. 10. Sheet resistance as a function of Ge composition for two different annealing methods.

These results revealed that sheet resistance depends on Ge composition and also that the dopant activation was dramatically enlarged using an excimer laser-annealing process, because the specification depth (<20 nm) of the Si/SiGe layer, which depends on the laser energy intensity, was melted and re-organized and then the latent heat assisted in the thermal diffusion.

A typical XRD rocking curve of the Ge content of the sample with ELA and spike RTA is shown in Fig. 11. The Ge and phosphorus was distributed throughout the melt, and the melt became progressively more concentrated with impurities. For this reason, the Ge contents dramatically improved using ELA. Furthermore, the curve of the laser-annealed sample with sharp, narrow peaks exhibited an abrupt doping profile.

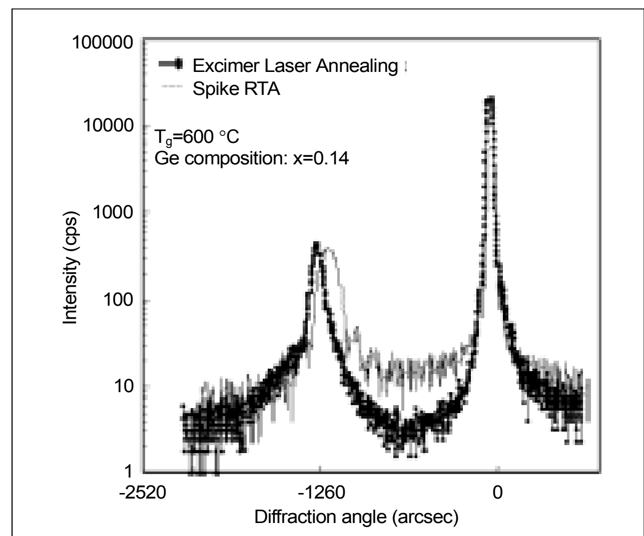

Fig. 11. X-ray rocking curves of SiGe films after laser annealing and spike RTA, respectively.

These results clearly demonstrate that the electric properties of SiGe SEG dramatically improve by using LA-SiGe SEG technology. In addition, we consider that the ELA not only assisted the in situ doped SiGe SEG activation, but also the SiGe epitaxial growth.

V. Conclusions

$Si_{(1-x)}Ge_x$ is a good material for progressive microelectronic components like heterojunction bipolar transistors and hetero-field effect transistors. The electrical and optical properties of these materials are influenced by Ge composition and well-controlled abrupt doping transitions. For this work, with experiments and analyses, we presented both an in situ doped SiGe selective epitaxial growth technique using a UHV-CVD apparatus and an abrupt annealing technique using an excimer

laser system.

Furthermore, using LA-SiGe-SEG technology, we achieved a relatively high Ge composition, a highly doped impurity concentration, and a low sheet resistance, which we characterized using x-ray the diffraction method, 4-point prove station, and SIMS. This technology provided superior immunity to TED, significantly higher doping concentration, abrupt doping profiles, and excellent electric properties compared to the conventional spike RTA. We confirmed that the laser annealed SiGe selective epitaxial growth method is a superior approach for achieving excellent characteristics for future devices.

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