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# Low temperature deposition of germanium on silicon using Radio Frequency Plasma Enhanced Chemical Vapor Deposition

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ABSTRACT

In this paper, a low temperature deposition of germanium (Ge) films on silicon (Si) is performed using Radio Frequency Plasma Enhanced Chemical Vapor Deposition (RF-PECVD). A two-step temperature technique and different $GeH_4$ flow rates have been employed during the deposition process. The structural and the optical properties of 700 nm Ge films have been investigated using high resolution scanning electron microscopy, atomic force microscopy, transmission electron microscopy (TEM), X-ray diffraction (XRD), Raman spectroscopy, and variable angle spectroscopic ellipsometry. Study of the surface morphology of low temperature Ge seed layer revealed that a surface roughness as low as 0.5 nm can be achieved with in-situ low temperature annealing in rich $H_2$ chamber. Also, the fast Fourier transform pattern taken at the same area imaged by TEM for the seed layer exhibited crystalline nature due to the hydrogen induced crystallization. In addition, the RF-PECVD method promotes the nanocrystals growth at low temperature via plasma contribution. The XRD data shows that polycrystalline Ge layers with four different orientation and average crystallizes size of 43 nm on Si substrate is achieved. Furthermore, the post annealing treatment of the films at $T < 600$ °C enhances its electrical and transport characteristics. The optical characteristics of the Ge-on-Si shows high absorption coefficient (approximately one order of magnitude higher than bulk Ge at 1.5 μm) in the near-infrared (1.5–1.6 μm).

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## 1. Introduction

Growth of germanium (Ge) on silicon (Si) substrate is a key approach for the development of future high-speed photonics and electronic devices [1–3]. The bulk hole and electron mobility of Ge are approximately four and two times higher than conventional Si channel, respectively. Moreover, Ge has a room temperature direct band gap of 0.8 eV (~1.55 μm) which is only separated by 0.14 eV from its indirect band gap (0.67 eV), therefore it acts as a strong absorber in the near-infrared light spectrum. In the context of these optical properties, Ge is an essential material in photodetectors operating in low loss window (1.3–1.5 μm) of the silica fibers [4–6]. Additionally, Ge is extensively used in growing III–V material where the lattice mismatch between III–V materials and Ge is negligible. However, fundamental issues with Ge such as the lack of stable germanium native oxide, its water solubility, and the poor physical and electrical properties of high κ oxide/Ge interfaces make it difficult to fabricate high-quality electronic or optoelectronic devices [7]. Furthermore, heteroepitaxial growth of high-quality films on silicon is very challenging due to the 4.2% lattice mismatch between the two materials [8,9].

Several techniques for fabricating and optimizing the growth of Ge on Si have been adopted. Conventionally, a graded SiGe buffer layers are grown to reduce the defects level due to lattice mismatch, followed by Chemical-Mechanical Polishing process to form a smooth surface for the next growth step. However, these layers can be as thick as 10 μm [10]. Furthermore, direct growth of pure Ge layers on silicon has been reported using Ultra-High Vacuum Chemical Vapor Deposition (UHVCVD) [11], Low Pressure Chemical Vapor Deposition (LPCVD) [12] and Reduced Pressure Chemical Vapor Deposition (RPCVD) [13]. Employing two-step growth process starts with low temperature layer acts as a seed layer and followed by high temperature step and cyclic annealing process have also been performed [14]. In addition, multiple steps of growth and high temperature hydrogen annealing has been reported to reduce dislocation density [15]. However, temperatures as high as 650 °C were used in performing the deposition. The high temperature processes used for direct growth of Ge on Si causes a lot of problems in the fabricated films, in addition they can hardly compatible with standard Si technology. Being able to achieve high quality Ge-on Si layers at low cost and with low thermal budget is a main concern in Ge-based devices. The goal is to produce a Ge layer with low surface roughness and an acceptable threading dislocation density ($TDD < 10^7$ $cm^{-2}$) values at low deposition temperature. Compared to high temperature UHVCVD, RPCVD and ultra-high vacuum Molecular Beam Epitaxy, Radio Frequency Plasma Enhanced Chemical Vapor Deposition (RF-

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PECVD) has an advantage of depositing Ge at 400° °C [16]. However, a detailed study of Ge-on-Si growth using RF-PECVD requires further investigation. Several studies have reported a two-step growth method [14,17]. However, a high-temperature process during both the film deposition and the post annealing process is required. Moreover, the germanium flow rate was not changed during these process.

In this paper, we present a comprehensive characterization of the structural and optical properties of low-temperature growth of pure Ge layers on 〈100〉 p-type Si wafer using RF-PECVD. The growth has two-step deposition method. In the first step, a low-temperature Ge deposition of 350 °C at high $GeH_4$ flow are carried out. This process was then followed by a higher temperature of 500 °C and low $GeH_4$ flow rate step. A cyclic annealing at low temperature was performed after the low temperature step. The structural properties of the grown Ge layers (defects, crystallinity, strain, and roughness) are carried out using transmission electron microscopy (TEM), X-ray diffraction (XRD), Raman spectroscopy, and atomic force microscopy (AFM) techniques. Furthermore, its optical absorption quality is tested in the C and L telecom bands.

## 2. Experimental details

A 6 inch (100) boron doped Si wafer with resistivity of 0.01–0.02 $\Omega\cdot$cm is used as a starting substrate for the Ge growth. To achieve a high-quality Ge layer, the substrate surface should be free from contamination and native $SiO_2$. Therefore, a pre-growth cleaning process is performed, where the wafer is ultrasonicated in acetone bath and rinsed with isopropanol and distilled water, followed by 60 s dip in diluted hydrofluoric acid (HF) 1:10 solution. After being cleaned, the wafer is loaded immediately to a load lock of an Oxford Instrument System 100 PECVD activated by 13.56 MHz radio frequency signal. Fig. 1a and b summarize the two-step process of the Ge growth. In step one (low temperature (LT), high rate (HR)) the deposition was performed at 350 °C with 3 sccm flow of $GeH_4$. This step is followed by an in-situ annealing at 350 °C using 20 sccm of $H_2$ and 200 sccm of Ar for 10 min. Some samples are grown without in-situ annealing for comparison. After this, step two (high temperature (HT), low rate (LR)) of the Ge deposition starts immediately without removing the wafer from the system. The Ge growth carried out at 500 °C with 1 sccm of $GeH_4$. With these two steps one cycle of Ge growth is done. For thicker films, step two of growth can be used for longer time. Furthermore, in the two-steps of Ge deposition the radio frequency power was fixed at 20 W, and the chamber pressure was set to 1000 mT with $H_2$ gas flow of 100 sccm and Ar gas flow of 100 sccm. The structural characterization of the Ge layers was carried out using a high resolution scanning electron microscopy (HRSEM) with an elementary dispersive spectroscopy (EDS) facility to verify the film thickness, the deposition rate, and the films constituents. To investigate the crystallinity and the crystallographic orientation of Ge layers, a $\Omega$-2θ scan were performed on XRD Empyrean from PANalytical. A 2° offset between the X-ray source and the detector is made to reduce the reflected signal from the high crystalline Si wafer at (004). Raman spectroscopy (Witec Alpha 300-Raman, 532 nm wavelength laser, power < 75 mW) is used to study the films vibrational modes. Moreover, tapping mode atomic force microscopy measurements are carried out using CSI instrument AFM Nano-Observer. Finally, cross sectional transmission electron microscopy imaging was performed using a FEI Tecnai TF-20 FEG/TEM operated at 200 kV in bright-field (BF) TEM mode, and high-resolution (HR) TEM mode.

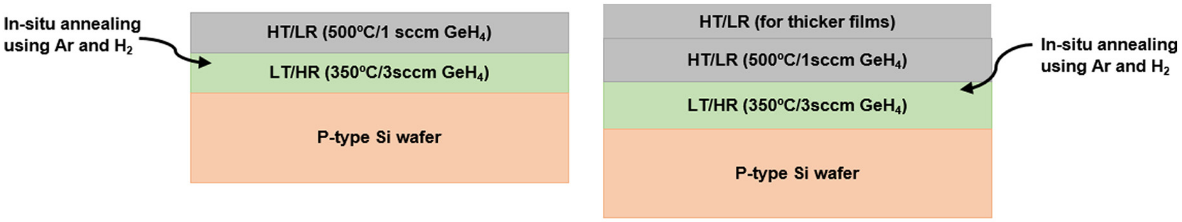
In order to study the optical absorption quality of the Ge layers, the absorption coefficient are measured using a tunable laser with wavelength window of 1.5–1.6 μm. The laser light is sent to the sample and the attenuation is recorded at the other side using a calibrated photo detector. Additionally, the optical parameters (index of refraction, optical band gap) of the grown Ge layers are extracted using J.A. Woolam Variable Angle Ellipsometer (VASE).

## 3. Results and discussion

### 3.1. HRSEM measurements

It is well known that Ge growth on Si follow the Stranski-Krastanov (SK) mechanism [18–20]. To prevent the clustering of the Ge and 3D island formation, in our first growth step a low temperature of 350 °C and high Ge atomic density are employed. As a result, the Ge atoms do not possess enough energy and maintain low mobility state. Furthermore, this helps in forming a continuous packed layer, where this seed film strongly influences the surface morphology and crystallinity of the second growth. It has been reported that a high Ge growth rate results in voids, where after exceeding a critical thickness they begin to form to relive the stress in the Ge layer [8,13]. In order to reduce the voids formation, the $GeH_4$ flow rate in the second deposition step was decreased to less than half compared to the first step. Furthermore, a higher deposition temperature of 500 °C is used to improve the crystallinity. Fig. 2 shows HRSEM cross section images of the deposited Ge films on Si. Based on those images, and the deposition time, it is estimated that the growth rate is 18.6 nm/min and 7.3 nm/min for LT/HR and HT/LR steps, respectively.

During the Ge film growth, in-situ thermal annealing is applied after the first growth step to study the temperature effect on the surface roughness and nucleation of the Ge layer. The temperature treatment is performed in a hydrogen rich environment, where 20 sccm of $H_2$ and 200 sccm of Ar are introduced for 10 min during the annealing. The hydrogen plays a role in increasing the Ge atoms surface mobility by lowering its diffusion barrier during the annealing process [21,22]. Furthermore, the annealing can help in smoothing the surface for next growth step. It also helps redistributing the dislocation by allowing them to propagate toward the edge of the substrate. However, if the first deposition of Ge (seed layer) is performed at $T > 400$ °C, a 3-dimensional island growth will occur which can lead to a rougher surface [23]. In this growth we started with Ge seed layer and deposited at low temperature of 350 °C. It should be noted that the EDS analysis does not show impurities like (H, O, and C) in the grown layer, although the system is not an UHV system. The Al peak appeared in the EDS spectrum is from the SEM 90° Aluminum stub which is used to mount the sample in to the SEM stage.



(a) (b)

**Fig. 1.** Schematic representation of Ge two-step growth. (a) One cycle of deposition, (b) growth of thick films.

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