Electrical and Structural Analysis on the Formation of n-type Junction in Germanium

Umar Abdul Aziz1, Nur Nadhirah Mohamad Rashid1, Siti Rahmah Aid1, Anthony Centeno1, Hiroshi Ikenoue2 and Fang Xie3

1Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
2Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka, Japan
3Department of Material, Imperial College London, England, United Kingdom

E-mail: sitirahmah.aid@utm.my

Abstract. Germanium (Ge) has re-emerged as a potential candidate to replace silicon (Si) as a substrate, due to its higher carrier mobility properties that are the key point for the realization of devices high drive current. However, the fabrication process of Ge is confronted with many problems such as low dopant electrical activation and the utilization of heavy n-type dopant atoms during ion implantation. These problems result in more damage and defects that can affect dopant activation. This paper reports the electrical and structural analysis on the formation of n-type junction in Ge substrate by ion implantation, followed by excimer laser annealing (ELA) using KrF laser. ELA parameters such as laser fluences were varied from 100 – 2000 mJ/cm² and shot number between 1 – 1000 to obtain the optimized parameter of ELA with a high degree of damage and defect removal. Low resistance with a high degree of crystallinity is obtained for the samples annealed with less than five shot number. Higher shot number with high laser fluence, shows a high degree of ablation damage.

1. Introduction

The International Technology Roadmap for Semiconductor (ITRS) has stated that traditional scaling of planar silicon Metal Oxide Semiconductor (Si-MOS) has reached its potential downscaling limit. Further downscaling will lead to the Short Channel Effect (SCE) that will result in an increase of devices leakage current [1–4]. This leakage current will increase the power consumption of devices while reducing the performance of the device. High drive current capability of devices without further downscaling process can be realized by increasing the carrier mobility in the substrate. Germanium (Ge) has emerged as one of the potential candidates to replace Si as a substrate for MOS transistor, due to its higher electrical carrier mobility (3900 cm²/ V.s for electrons and 1900 cm²/ V.s for holes) [5]. Furthermore, its similarity with the conventional Si will ease the replacement process in manufacturing lines [6–8].

The fabrication of Ge-based MOS transistor presents several problems associated with poor dopant solubility, low dopant electrical activation level and large dopant diffusion coefficient. All of these problems will limit the high drive current capability of the devices and increase leakage current [9–12]. Moreover, the fabrication of n-MOS transistor is more problematic than p-MOS due to the utilization of
heavy dopant ions i.e. arsenic (As) and antimony (Sb) during the ion implantation process resulting in more damage and defects [12]. The damages and defects will interact with the dopant atoms during thermal annealing and result in electrical deactivation. Therefore, further optimization of thermal annealing is important to achieve high dopant concentration profile in order to realize a higher electrically active carrier concentration as well as damage and defect removal in the substrate after ion implantation process.

Recently, excimer laser annealing (ELA) has gained interest compared to other conventional thermal annealing i.e. Rapid Thermal Annealing (RTA) and Furnace Annealing (FA) since it can achieve higher carrier concentration with a high level of damage/defect removal [13–15]. Due to Ge low melting point, ELA is very efficient for resolidification of ion-implanted Ge substrate at lower laser energy density compared to Si [16].

This paper reports the electrical and structural analysis of n-type junction in Ge substrate by ion implantation process followed by KrF excimer laser. Laser fluences and shot numbers were varied to find the optimized parameter of laser annealing. The annealed sample was experimentally analyzed by I-V characteristics for the resistance value, FESEM for surface images and Raman spectroscopy for the recrystallization. The result of the analysis for the annealed sample is discussed.

2. Experimental Details
Ge (100) wafer was implanted with P at an energy of 20 keV and dose concentration of $3.5 \times 10^{14}$ cm$^{-2}$. This combination is important in order to achieve simulated maximum dopant concentration of $1 \times 10^{20}$ cm$^{-3}$ [17]. 7° tilt angle was selected to minimize the channeling effect during the ion implantation process [18–19]. Prior to the thermal annealing process, Ge implanted sample was cleaned using de-ionized water for 1 minutes. Laser thermal annealing was then performed using KrF excimer laser ($\lambda = 248$ nm) with a pulse duration of 55 ns in an ambient atmosphere. The laser spot size is 300 µm $\times$ 300 µm. Laser fluences were varied from 100 to 2000 mJ/cm$^2$ and shot numbers varied from 1 to 1000 shots. Current-Voltage (I-V) measurement were taken for each annealed spot. Selected area was measured by Field Emission Scanning Electron Microscope, FESEM to obtain surface morphology of the annealed spots. Recrystallization of annealed sample was then characterized using Raman Spectroscopy.

3. Results and Discussion
Each laser matrix spot (300 µm $\times$ 300 µm) was analysed by I-V characteristics in order to measure the resistance of implanted layer. The result of resistance obtained from I-V characteristics is shown in figure 1. Resistance of non-irradiation area is also included as a reference. Stable tendency of resistance with value of less than $1.0 \times 10^3 \ \Omega$ can only be achieved when the shot number were below five. These low resistance values from I-V characteristics indicated that high level of activation can be obtained after the laser annealing process. This activation takes place by dopant substitution onto the lattice site during the recrystallization process. The level of damage removal can be expected to be higher in these samples. On the other hand, high laser fluence with high shot number show fluctuating resistance. This is due to the ablation damage to the annealed spot as observed from FESEM analysis.

Figure 2 shows the FESEM images of laser annealing spot for various fluence and shot number. Higher laser fluence and shot number results in high degree of ablation damage and surface roughness; as observed from figure 2 (a) with 2000 mJ/cm$^2$ and 1000 shots. This roughness damage leads to the dopant loss which reduced the concentration of dopants in the substrate. Ablation damage was reduced significantly with reduced laser fluences and shot numbers as observed from figure 2(a-d).

Due to the usage of high laser fluence and shot number, it can be considered that the energy deposition and surface temperature of annealed spot increased [20]. Melted substrate merge together resulting into bump formation on the outer layer of annealed spot and decrease the dopant substrate density; as can be observed from the rough surface of figure 2(a). The decrease in substrate density may results in the dopant loss, which subsequently leads to decrease of the attained dose of implanted dopant near the surface. Hence, the increase in resistance value as shown in figure 1. Bump formation is related to increase in local volume of the substrate, due to increased stresses by laser heating [20]. This can be related to the
surface roughness that eventually will affect the stability and accuracy of electrical measurement in the samples (refer to figure 1). Therefore, it is important to select appropriate laser parameter (i.e. laser fluence and shot number) to reduce the laser annealing damages that affect the physical and electrical characteristics of the fabricated sample.

![Figure 1](image1.png)

**Figure 1** Fluence vs resistance graph obtains from I-V characteristics for ELA center parameter

![Figure 2](image2.png)

**Figure 2** FESEM images of laser annealing spot (300 µm × 300 µm) of difference laser fluence and shot number (a) 2000 mJ/cm² with 1000 shots (b) 1000 mJ/cm² with 100 shots (c) 500 mJ/cm² with 5 shots and (d) 300 mJ/cm² with 5 shots

Figure 3 shows the Raman spectroscopy of the samples annealed with shot number below five; with laser fluences from 300 to 2000 mJ/cm². The broad peak phase of damage region (i.e. amorphous Ge, \(a\)-Ge), is at 270 cm⁻¹ while for crystalline Ge (c-Ge) region is around 300 cm⁻¹. Peak shift of c-Ge samples can
be observed when the ELA were performed with laser fluences above 300 mJ/cm²; and shot number ranging from two to five. This indicates recrystallization of damage layer has occurred with the degree of crystallinity improved along with the laser fluences. However, ablation damage might occurred in the sample annealed with higher laser fluence. This should be taken into consideration during the parameter selection.

The significant of high degree of crystallinity with lower resistance can be explained by the melt-regrowth model [21]. When a-Ge were completely melted due to ELA, epitaxial regrowth of the melted region occurred, which enable high activation of the dopants. A good resolidification indicates good crystallinity structure that will provide much lower leakage current.

Figure 3 Raman spectra of annealing sample at laser fluence vary from 300 to 1000 mJ/cm² with shot number vary from two to five

4. Conclusion
In this work, fabrication of Ge pn junction using KrF excimer laser was demonstrated. Optimization of laser thermal annealing was performed by varying the laser fluences and shots number. The electrical and structural analysis was performed to obtain optimized parameter of laser annealing. It is found that low resistance with a high degree of crystallinity is obtained for the samples annealed with less than five-shot number. Higher shot number with high laser fluence, shows a high degree of ablation damage. For the future works, samples will be fabricated with lower energy fluence (i.e. lower than 500 mJ/cm²) with shot number below five shots to measure sheet resistance, \( R_s \) of implanted layer with higher accuracy. Recrystallization layer will also be quantitatively analysed using Ellipsometry to support Raman spectroscopy analysis.

Acknowledgments
This work is supported by Imperial College Global Engagement Grant, Universiti Teknologi Malaysia International Networking Grant (PY/2015/04262), Takasago Research Grant (OTR) (PY/2015/05503; Vote No: 4B211) and Ministry of Education, Malaysia, Universiti Teknologi Malaysia Research University Grant Tier 1 (PY/2016/06558; Vote No: 14H01). The authors would like to acknowledge the support by Prof. Dr. Satoru Matsumoto and Mr. Akira Suwa (Department of Gigaphoton Next GLP, Kyushu University) for the contributions in this work.

References
[1] Information on ITRS 2010 Report at www.itrs.net
[2] Aid S R, Matsumoto S and Fuse G 2011 Physica Status Solidi A. 208 1646-1651
[3] Aid S R, Matsumoto S, Fuse G, and Sakuragi S 2011 Physica Status Solidi A. 208 2772-2777
[4] Aid S R, Hara S, Shigenaga Y, Fukaya T, Tanaka Y, Matsumoto S, Fuse G and Sakuragi S 2013 Japanese J. of Appl. Phys. 52 026501
[5] Sze S M, Ng K K Physics of Semiconductor Devices (New York: Wiley- Interscience)
[6] Shang H, Frank M M, Gusev E P, Chu J O, Bedell S W, Guarini K W and Leong M 2006 IBM J. Res. & Dev. 50 337
[7] Lee C H, Nishimura T, Tabata T, Wang S K, Nagashio K, Kita K, and Torium A 2010 IEDM. 18.1.1
[8] Simoen E and Vanhellemont J 2009 Journal of Appl. Phy. 106 103516
[9] Thareja G, Liang J, Chopra S, Adams B, Patil N, Cheng S L, Nainani A, Tasyurek E, Kim Y, Moffatt S, Brennan R, McVittie J, Kamins T, Saraswat K and Nishi Y 2010 IEDM 10.5.1
[10] Takagi S, Tezuka T, Irisawa T, Nakaharai S, Numata T, Usuda K, Sugiyama N, Shichijo M, Nakane R and Sugahara S 2007 Solid-State Electron. 51 526
[11] Mirabella S, De Salvador D, Napolitani E, Bruno E and Priolo F 2013 J. of Appl. Phy. 113 031101
[12] Kim J, Bedell S W and Sadana D K 2011 Appl. Phy. Lett. 98 082112
[13] Shayesteh M, O’ Connell D, Gity F, Stud. Mem, IEEE, Murphy-Armando P, Yu R, Huet K, Toqué-Tresonne I, Cristiano F, Boninelli S, Henrichsen H H, Nielsen P F, Petersen D H and Duffy R 2014 IEEE Trans. on Elect. Dev. 61 4047
[14] Hellings G, Rosseel E, Simoen E, Radisic D, Peterson D H, Hansen O, Nielsen P F, Zschatsch G, Nazir A, Clyssye Vandervorst T W, Hoffmann T Y and De Meyer K 2011 Elec. Solid-State Lett. 14 H39-H41
[15] Milazzo R, Napolitani E, Impellizerri G, Fisicaro G, Boninelli S, Cuscuna M, De Salvador D, Mastromatteo M, Italia M, La Magna A, Fortunato G, Priolo F, Privitera V and Carnera A 2014 J. of Appl. Phy. 115 053501
[16] Wang C, Li C, Huang S, Lu W, Yan G, Zhang M, Wu H, Lin G, Wei J, Huang W, Lai H and Chen S 2014 Appl. Surface Science 300 208-212
[17] Aziz U A, Arissa N F, Aid S R, Yahaya H, Centeno A, Matsumoto S, Uedono A and McPhail D 2015 MJJIC 2015
[18] Chui C O, Kulig L, Moran J and Tsai W 2005 Appl. Phys. Lett. 87 09190
[19] Ioannou N, Skarlatos D, Tsamis, Krontiras A, Georga S N, Christofi A and McPhail D S 2008 Appl. Phy. Lett. 90 101910
[20] Iqbal M H, Bashir S, Rafique M S, Dawood A, Akram M, Mahmood K, Hayat A, Ahmad R, Hussain T and Mahmood A 2015 Appl Surf. Sci. 344 146-158
[21] Preston J S and van Driel H M 1984 Phys. Rev B. 30 1950–1956