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Hot-C^+-Ion Implantation Optimization for Forming Nano-SiC Region at Surface (100)SOI Substrate

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Abstract

We experimentally studied a hot-C^+-ion implantation (HCI) optimization for forming nano-SiC regions in a (100)SOI substrate, to improve the photoluminescence (PL) emission for a future Si-based photonic device. We successfully optimized that the HCI temperature T is about 700°C and the C ion dose D_C is 4×10^{16}cm^{-2} to realize strong PL intensity I_{PL} from an approximately 1.5-nm-thick C atom segregation layer (CSL) which is analyzed by an atom prove tomography (APT) at the surface oxide (SOX)/Si interface. Corrector-spherical aberration TEM (CSTEM) observation also showed that both a 4H- and 3C-SiC (silicon carbide) nano-areas are partially formed near both the SOX/Si and buried-oxide (BOX)/Si interfaces in the CSL, and PL photons are mainly emitted from these SiC areas.

I. Introduction

Recently, we experimentally studied a $Si_{1-Y}C_Y$ layer fabricated by hot-$^{12}C^+$-ion implantation (HCI) into a (100)SOI at 900°C in a wide range of $0.01<Y\leq0.25$ and $0.5\leq d_S\leq20$nm, where d_S is the SOI thickness [1], [2]. We demonstrated very large bandgap E_G (≈3eV), and very strong I_{PL} from the near-UV to visible region (>400nm) of the $Si_{1-Y}C_Y$ layer, which drastically increases with increasing Y in $Y\leq0.25$. C atoms segregate at both the SOX/Si and BOX/Si interfaces, resulting in partial formation of 3C-SiC at the BOX/Si interface [2]. Strong PL emission, which is about 100 times as large as that of 2D-Si [2], originate from the C segregation layer (CSL). Thus, the $Si_{1-Y}C_Y$ technique is very suitable for both a new E_G engineering for high-speed source-heterojunction devices (SHOT) [3] and visible Si-based photonic devices [4].

In this work, we experimentally optimized the HCI process of T and D_C of a $Si_{1-Y}C_Y$ layer at the surface (100) SOI substrate to realize stronger I_{PL} for a Si photonic device, as well as to study the nano-SiC quality in the CSL, using the analytical methods of ATP [5], CSTEM, and PL.

II. Experiment Procedure

$Si_{1-Y}C_Y$ layers were fabricated by HCI into (100) bonded SOI substrate with an about 100-nm thick SOX [2], where $2\times10^{16}\leq D_C\leq7\times10^{16}$cm^{-2}. The peak recoil energy E_R of C^+ ions exists in the thick SOX, resulting in lower ion-implantation-induced-damege (IID) in the Si layer. In this work, we used the thin (8nm) and thick (20nm) Si layer of SOI substrate. The SOI substrate temperuture T at HCI was varied from 500 to 1000°C, to study the nano-SiC formation as well as the recover of the IID in the Si layer.

The 3D distribution of C atoms in 8nm and 20nm SOIs was mainly analyzed by APT, where the spatial resolution is 0.5nm and the detection limit of C atoms is 5×10^{18}cm^{-3} [5]. The material structures of the CSL was evaluated by CSTEM and the electron diffuraction (ED) patterns obtained by fast-Fourier-transform (FFT) analysis of the lattice spots of CSTEM. d_S was evaluated by the UV-visible reflection method [1] as well as CSTEM.

PL and Raman properties of $Si_{1-Y}C_Y$ layers were measured at room temperatrure, where the excitation laser energy E_{EX} was 3.8eV and the laser diameter was 1μm. At E_{EX}=3.8eV, the PL photons were mainly emitted from the CSL near the SOX/Si interface, because the penetration length λ_{EX} of 3.8eV in Si layer is only 8nm [2]. The PL spectrum in a wide range of photon wavelengths λ_{PL} from the near-UV to NIR regions was calibrated using a standard illuminant [2].

III. HCI Optimization

A. D_C Dependence of PL Property

The APT analysis for the Y depth profile of a 8-nm SOI shows that very narrow 1.5-nm-thick CSL with Y>0.2 were formed at both the SOX/Si (peak-Y=0.25) and BOX/Si (peak-Y=0.3) interfaces, just after HCI process **(Fig. 1)**. Thus, we can detect PL emission from the CSL at the SOX/Si interface region even in a thick SOI.

The D_C dependence of PL spectrum clearly shows that the D_C of 4×10^{16}cm^{-2} is the optimum dose for stronger I_{PL} **(Fig. 2)**, which is attributable to the following mechanisms. At $D_C\leq4\times10^{16}$cm^{-2}, $I_{PL}\propto\exp(11.7Y)$ [2], because a SiC area can be formed in the CSL only at higher D_C condition. On the other hand, at $D_C>4\times10^{16}$cm^{-2}, the Si crystal quality is degraded with increasing D_C, resulting in the I_{PL} reduction. Hereafter, we will discuss the physical properties of a $Si_{1-Y}C_Y$ layer at the optimized D_C of 4×10^{16}cm^{-2}.

B. Material Structure: 4H-/3C-SiC Formation

The APT result in the thin SOI plane (xy plane) shows that C atoms partially cluster [6] in a low-C Si layer without CSL (inside the circles **(Fig.3(a))**, the cluster size is approximately 5nm. Thus, the C density fluctuates in the Si layer. As a result, the CSTEM also shows that approximately 5-nm-SiC dots, shown as moire patterns interfered by two layers of 3C-SiC and Si, were formed in Si layer **(Fig.3(b))**. The SiC dots with larger E_G is expected to affect the PL spectrum. Moreover, the Y fluctuates and is varied from 0.1 to 0.2 even in the surface CSL **(Fig.3(c))**. In the back CSL, the Y is also varied from 0.15 to 0.25. Thus, the clustered C atoms bind to Si atoms, resulting in the partial formation of SiC in CSL.

Actually, according to the CSTEM analysis of the surface CSL and the electron diffraction (ED) patterns obtained, both 4H- and 3C-SiC areas were partially formed **(Figs.4)**, but the density of 3C-SiC, N_{3C} was higher than that of 4H-SiC, N_{4H}. However, the clear ED patterns of SiC are rarely observed, because the ED patterns in the CSL are obtained by the interference of the multiple SiC and Si layers. We also confirmed the partial formation of both 4H-/3C-SiC in the back CSL. Thus, the implanted C atoms segregate both at the SOX/Si and BOX/Si interfaces and cluster, resulting in the partial formation of both 4H-/3C-SiC areas. The surface (PL1) and back CSL (PL2) are considered to emit strong PL photons **(Fig.5)**, and the measured PL photons in this study are mainly emitted from PL1 area, because of very small λ_{EX} of 8nm.

C. T Dependence of PL Property

The PL spectrum of both 8nm and 20nm $Si_{1-Y}C_Y$ layers strongly depends on the T **(Figs.6 and 7)**. The I_{PL} increases with decreasing T in $T\geq700$°C, but decreases at T=500°C **(Fig. 7(a))**. Thus, the T of about 700°C is the optimum temperature. Small I_{PL} at T=500°C is attributable to the C^+ ion implantation induced damage in Si layer, since the FWHM of Si Raman peak increases with decreasing T **(Fig. 7(b))**. On the other hand, the rapid reduction of I_{PL} at T=1000°C is possibly attributable to the reduction of the SiC formation at high T condition. In addition, the PL spectrum profile depends on d_S and has two peaks at d_S=20nm **(Figs. 6)**, which possibly relates to the d_S dependence of N_{4H}/N_{3C} and the E_{PH} of ~3.1eV is probably the E_G of 4H-SiC [7]. Thus, N_{4H}/N_{3C} increases with decreasing d_S.

At d_S of both 8 and 20nm, PL spectrum in the whole range of T can be well fitted by two Gaussian curves of I_L with lower E_{PH} (E_L) and I_H with higher E_{PH} (E_H) **(Figs.5, 8(a), 8(b))**. Here, we compare experimental E_L and E_H with the expanded E_G of nano-dots of 3C-SiC (E_{3C}) and 4H-SiC (E_{4H}) [7]. E_L and E_H are almost independent of T except the E_H at T=1000°C, and thus the E_G of a $Si_{1-Y}C_Y$ layer is not affected by T **(Fig.9(a))**. It is noted that the E_L and E_H values are close to the E_{3C} and E_{4H} values, respectively. Thus, it is possible that the E_L and E_H regions of a $Si_{1-Y}C_Y$ layer are mainly composed of a 3C- and 4H-SiC nano-areas, respectively. However, I_L (3C-SiC) and I_H (4H-SiC) strongly depend on T **(Fig.9(b))**. Thus, the T dependence of I_L and I_H relates to that of N_{3C} and N_{4H}, respectively. Thus, the optimum T is about 700°C for forming a 3C- and 4H-SiC nano-regions in the HCI process of SOI.

IV. Conclusion

In this work, we experimentally optimized the HCI process of D_C and T in a (100) SOI substrate to form nano-SiC regions as well as to realize higher I_{PL} for a Si-based photonic device. As a result, the optimum D_C and T are about 4×10^{16}cm^{-2} and 700°C, respectively. In addition, we experimentally confirmed the partial formation of both nano 3C- and 4H-SiC areas in the CSL at both the SOX/Si and BOX/Si interfaces.

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References: [1] T.Mizuno, JJAP **55**, 04EB02, 2016. [2] T.Mizuno, JJAP **56**, 04CB03, 2017. [3] T.Mizuno, JJAP **50**, 010107, 2011. [4] S. Saito, IEDM 2008, Paper 19.5. [5] http://www.nanoanalysis.co.jp/en/. [6] Y.Shimizu, APL **98**, 232101, 2011. [7] J.Fan, *Silicon Carbide Nanostructures* (Springer), 2014.

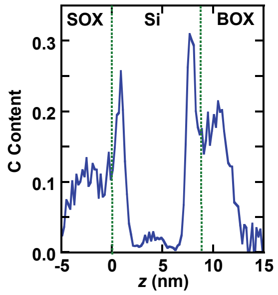

Fig.1 APT results of non-uniform depth z profile of C content Y (solid line) in a SOI layer, where T=800°C, D_C=4×10^{16}cm^{-2}, and d_S=8nm.

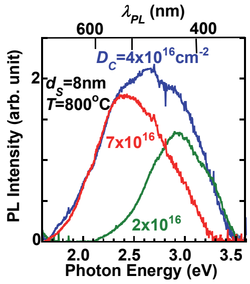

Fig.2 D_C dependence of PL spectrum, where d_S=8nm, T=800°C, and E_{EX}=3.8eV.

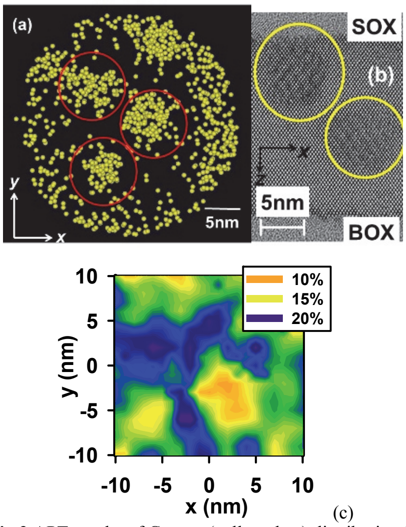

Fig.3 APT results of C atom (yellow dots) distribution in (a) the central region of a Si layer without the CSL and (c) 2D contour maps of Y (at.%) in the surface CSL, where T=800°C, D_C=4×10^{16}cm^{-2} and d_S=8nm. The circles in (a) show the C atom clustering (CAC). (b) CSTEM image of SiC dots inside circles in 20-nm SOI, where T=900°C and D_C=4×10^{16}cm^{-2}. The SiC dot size in (b) is approximately 6nm, which is almost the same as that of CAC in (a).

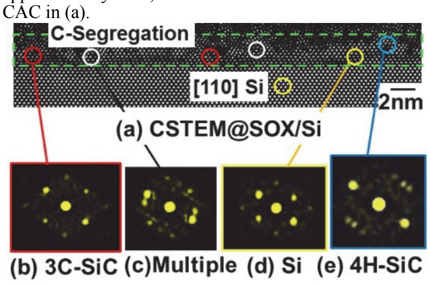

Fig.4 (a) CSTEM image of the cross section of the surface CGL, where T=900°C, D_C=4×10^{16}cm^{-2} and d_S=8nm. (b) (red circles), (c) (white circles), (d) (yellow circles) and (e) (blue circle) in (a) show the ED patterns of [110]3C-SiC, multiple layers of [110]3C-SiC/Si, Si, and [2$\bar{1}\bar{1}$0]4H-SiC, respectively, where the diameter of all circles is approximately 2nm.

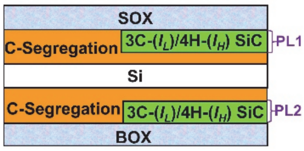

Fig.5 Schematic cross section of SOI layers with 4H-and 3C-SiC nano-regions in the CSL near both the SOX and BOX interfaces. PL1 and PL2 show the PL emission layers at the surface and back SiC regions, respectively. I_L and I_H are PL emissions from 3C- and 4H-SiC areas, respectively. Measured PL intensity is mainly emitted from the PL1 area, because of very small λ_{EX} of 8nm.

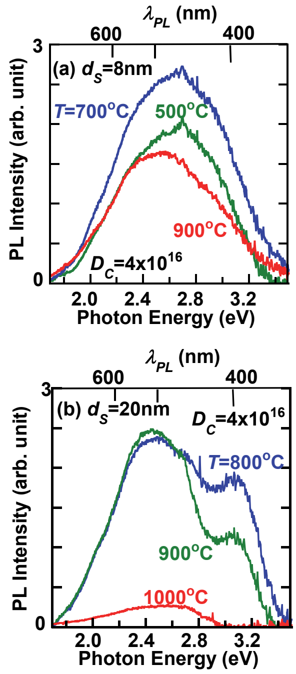

Fig.6 T dependence of PL spectrum of Si$_{1-Y}$C$_Y$ at (a) d_S=8nm and (b) 20nm, where D_C=4×10^{16}cm^{-2} and E_{EX}=3.8eV. The second peak in (b) is possibly attributable to the 4H-SiC dot with higher E_G [7].

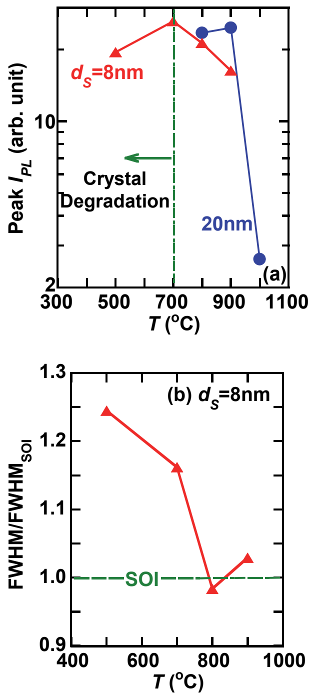

Fig.7 T dependence of (a) peak I_{PL} and (b) FWHM of Si Raman peak at d_S=8nm normalized by that of SOI, where D_C=4×10^{16}cm^{-2} and E_{EX}=3.8eV. Circles and triangles in (a) show the data of d_S=20nm and 8nm, respectively.

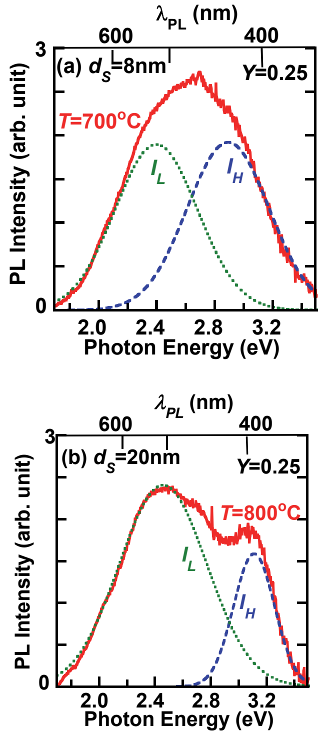

Fig.8 Experimental PL spectrum (solid line) of Si$_{1-Y}$C$_Y$ layer fitted by two Gaussian curves with low (I_L: dotted line) and high E_{PH} (I_H: dashed line) at (a) d_S=8nm and =700°C and (b) d_S=20nm and T=800°C, where D_C=4×10^{16} cm^{-2}.

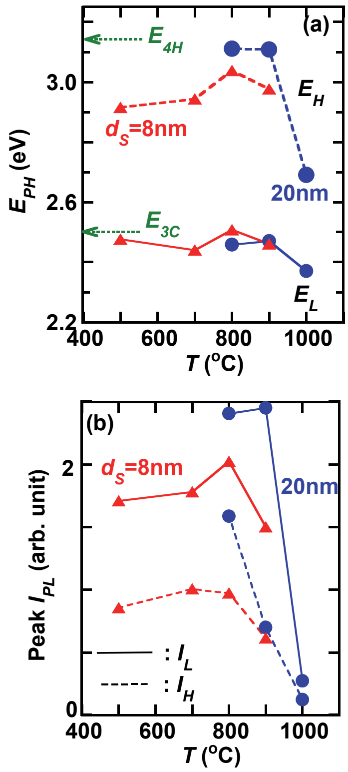

Fig.9 T dependence of (a) E_L and E_H, and (b) peak-I_L and I_H, where D_C=4×10^{16}cm^{-2}. Circles and triangles show the data at d_S=20nm and 8nm, respectively. The solid and dashed lines show the data of E_L and E_H, respectively. Arrows in (a) show the E_{3C} (≈2.5eV) and E_{4H} (≈3.15eV) of 2-nm SiC-dots [7].