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Characterization for N- and P-type 3C-SiC on Si (1 0 0) substrate with thermal anneal and pulsed excimer laser anneal

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ABSTRACT

Thermal and pulsed excimer laser treatments have been applied for the post-implant anneals of Al- and N-implanted 3C-SiC samples to recover crystal damage caused by the ion implantation. FTIR reflectivity spectra show that the thermal anneal carried out at 1350 °C for 30 min has the better damage recovery in a range of the reststrahlen bands of both Al- and N-implanted samples. However, shoulders in the XRD spectra caused by the implantation indicate that a thermal anneal cannot completely recover the damage throughout an entire sample. For the Al-implanted samples, laser pulses with various energy densities can move shoulders to higher 2θ angles and then merge shoulders with the major peaks at the total energy density of 583.7 J/cm^2. 150 shots of laser pulses at the energy density of 256 mJ/cm^2 and combining with other energy densities can be used to recover damage in a range of the reststrahlen band which is induced by laser irradiation. Furthermore, the damage caused by the implantation in N-implanted samples is not close to the major peak in the XRD spectra, which can be improved by the laser pulses as well, but not moved to higher 2θ angles. However, the applied energy densities create extra damage in a range of the reststrahlen band.

1. Introduction

Cubic silicon carbide (3C-SiC) is an attractive power semiconductor material because of it remarkable properties such as wide band gap, high thermal conductivity, and high breakdown field. Moreover, 3C-SiC epitaxial layers can be grown on a Si substrate, reducing the material cost. However, the 3C-SiC quality is influenced by the mismatch in lattice parameter and thermal expansion coefficient between 3C-SiC epilayers and Si substrates [1]. Furthermore, due to the short diffusion length of impurities in SiC materials, the elevated temperature implantation is the only method to incorporate impurities into SiC epilayers and to avoid forming amorphous layers [2,3]. However, crystal damage is inevitably induced by the implantation. Therefore, the post-implant anneal at extremely high temperature is needed to recover damage and activate dopants. Unfortunately, such a high temperature treatment will cause the sublimation of Si atoms on the surface, leading to step bunching and redistribution of the implanted dopants [3,4]. In addition, the highest anneal temperature of around 1400 °C for 3C-SiC is also limited by the melting point of Si substrates and the temperature may not be high enough to completely recover all damage in 3C-SiC [5]. Therefore, the pulsed excimer laser can be used for a post-implant anneal at a lower temperature to repair the lattice damage and activate dopants in doped regions [2–4,6–17]. Since pulsed excimer laser irradiation can accumulate enough energy within few nanoseconds into SiC surface of the specified area, the surface temperature can be very high. Because the heating time is very short, the vertical and lateral heat transfer is very limited [3,4]. Hence, the substrate can maintain a low temperature. In order to avoid surface ablation and also to recover damage and to activate dopants, a multiple energy irradiation method was used in this work [2,3]. Fourier transform infrared spectroscopy (FTIR) Raman spectroscopy and X-ray diffraction (XRD) were used to characterize the lattice modification induced by the ion implantation and pulsed excimer laser anneal. These measurements are non-destructive and have high resolution on lattice changes.

2. Experimental details

3C-SiC samples with a thickness of 5.5 μm were used for aluminum (Al) and nitrogen (N) ion implantation at 650 °C with multiple energies/doses. The energies are in the range of

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Table 1
Shots of laser pulses at various energy densities for the Al-implanted samples.

Sample	Shot						Summary (J/cm^2)
	Energy density (mJ/cm^2)						
	244	200	256	400	644	822	
Al-LA1	50	0	0	0	0	0	12.2
Al-LA2	100	0	0	0	0	0	24.4
Al-LA3	200	0	0	0	0	0	48.8
Al-LA4	200	300	0	0	0	0	108.8
Al-LA5	200	300	150	0	0	0	147.2
Al-LA6	200	300	150	300	0	0	267.2
Al-LA7	200	300	150	300	300	0	460.4
Al-LA8	200	300	150	300	300	150	583.7

20–360 keV and the total doses of Al and N are 10.2×10^{14} and 46.8×10^{14} cm^{-2}, respectively. The doping concentrations are designed for the P$^+$ and N$^+$ regions of DMOSFETs. The highest doping concentrations of Al- and N-implanted regions are about 1×10^{20} cm^{-3} simulated by Trim software. Following the elevated temperature implantation, the thermal anneal (TA) and pulsed excimer laser anneal (LA) were carried out for the post-implant anneals. The thermal anneal was carried out at a temperature of 1350 °C for 30 min; the KrF pulsed excimer laser manufactured by Coherent Inc. with multiple energy densities was then performed at a repetition rate of 10 Hz. Square areas of 9 mm^2 were exposed to various shots and energy densities of laser pulses at room temperature. A number of shots and energy density per shot for Al- and N-implanted samples are listed in Tables 1 and 2, respectively. The sample codes for Al- and N-implanted samples with the laser anneal are Al-LA1–8 and N-LA1–3, respectively. The energy densities were gradually increased to avoid surface ablation caused by a pulsed excimer laser anneal because a low energy density can repair the damage on the surface region so that the absorption coefficient will be reduced. Therefore, as the energy density increase, the annealed thickness can be deeper without ablation due to the low energy absorbed on the surface [3]. In order to investigate the recovery of damage caused by the implantation and anneals, as-grown and Al- and N-implanted samples without any anneals were used as reference. The sample codes for Al- and N-implanted samples without any anneal are Al-NA and N-NA, respectively; the sample codes for Al- and N-implanted samples with thermal anneals are Al-TA and N-TA, respectively. FTIR, XRD and Raman were undertaken right after each of laser anneals to investigate the influence of the energy densities and shots on damage.

3. Results and discussion

3.1. Al-implanted samples

Table 2
Shots of laser pulses at various energy densities for the N-implanted samples.

Sample	Shot			Summary (J/cm^2)
	Energy density (mJ/cm^2)			
	256	400	644	
N-LA1	200	0	0	51.2
N-LA2	200	300	0	171.2
N-LA3	200	300	300	364.4

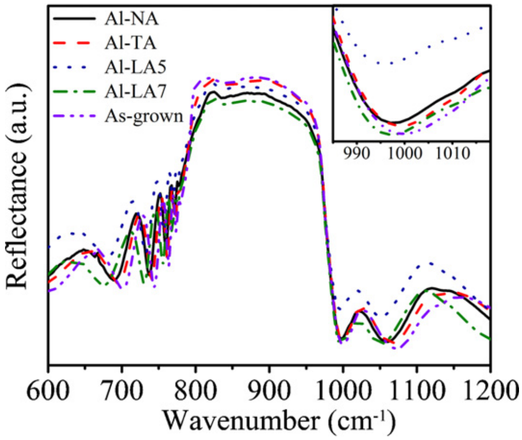

Fig. 1. The FTIR reflectivity spectra of an as-grown sample and Al-implanted samples without anneal (Al-NA), with thermal anneal (Al-TA) and laser anneals (Al-LA5 and Al-LA7).

Fig. 1 shows the FTIR reflectivity spectra of the samples as-grown, Al-NA, Al-TA Al-LA5, and Al-LA7. The FTIR reflectivity spectra of the sample Al-TA is very close to the as-grown one, indicating the damage in the range of the reststrahlen band is almost recovered by the thermal anneal [2,5,6]. The FTIR reflectivity spectra of the laser-annealed samples increase as the total energy density increases up to Al-LA5. Al-LA1–4 are not shown in Fig. 1. However, the FTIR reflectivity spectra then quickly decrease for the samples Al-LA6 and Al-LA7, below that of the sample, AL-NA, as shown in Figs. 1 and 2. This is because that the applied laser pulses cause extra crystal damage [2,5,6]. Therefore, the optimal energy densities and a number of shots for the laser anneal to recover damage should be located between Al-LA5 and Al-LA6. The FTIR reflectivity spectra of Al-implanted samples with the optimized laser anneal should be close to those of the as-grown and thermal-annealed samples. In addition, from the bottoms of the FTIR reflectivity spectra located around 1000 cm^{-1} in the inset in Fig. 1, it shows that only the sample Al-TA shifts to the higher values of wave numbers, indicating the higher free carrier concentration in this sample, compared with other samples [6,18]. The sample Al-LA5 with relative lower energy barely moves, indicating the activation is low. However, the sample Al-LA7 with relative higher energy even shifts to the left side due to more damage created by the laser irradiation, trapping the free carrier concentration [6].

It is worth mentioning that as the shots of laser pulses increase to 300 as listed in Table 1, the FTIR reflectivity spectra decrease due to the damage induced by the higher energy densities as shown in Fig. 2. The FTIR reflectivity spectra of Al-LA4 is lower than that of Al-LA3 because of the additional 300 shots of laser pulses at 200 mJ/cm^2; however, the FTIR reflectivity spectra of Al-LA5 is much higher than those of Al-LA3 and Al-LA4 by adding 150 shots of laser pulses at 256 mJ/cm^2. Once again, the FTIR reflectivity spectra of Al-LA6 and Al-LA7 are much lower than that of Al-LA5 due to extra 300 shots of laser pulses at 400 and 644 mJ/cm^2. The FTIR reflectivity spectra of Al-LA8 is higher than those of Al-LA6 and Al-LA7 by adding 150 shots of laser pulses at 822 mJ/cm^2, but still much lower that of Al-LA5 due to the damage induced by laser