Influence of Triangle Structure Defect on the Carrier Lifetime of the 4H-SiC Ultra-Thick Epilayer *

Ying-Xi Niu(钮应喜)[1,2], Xiao-Yan Tang(汤晓燕)[1**], Ren-Xu Jia(贾仁需)[1], Ling Sang(桑玲)[2], Ji-Chao Hu(胡继超)[3], Fei Yang(杨霏)[2], Jun-Min Wu(吴军民)[2], Yan Pan(潘艳)[2], Yu-Ming Zhang(张玉明)[1]

[1]*School of Microelectronics, Xidian University, the State Key Laboratory of Wide Band Gap Semiconductor Technology, Xi'an 710071*

[2]*State Key Laboratory of Advanced Power Transmission Technology, Global Energy Interconnection Research Institute, Beijing 102211*

[3]*Department of Electronic Engineering, Xi'an University of Technology, Xi'an 710048*

(Received 17 April 2018)

Effect of triangle structure defects in a 180-μm-thick as-grown n-type 4H-SiC homoepitaxial layer on the carrier lifetime is quantitatively analyzed, which is grown by a horizontal hot-wall chemical vapor deposition reactor. By microwave photoconductivity decay lifetime measurements and photoluminescence measurements, the results show that the average carrier lifetime of as-grown epilayer across the whole wafer is 2.59 μs, while it is no more than 1.34 μs near a triangle defect (TD). The scanning transmission electron microscope results show that the triangle structure defects have originated from 3C-SiC polytype and various types of as-grown stacking faults. Compared with the as-grown stacking faults, the 3C-SiC polytype has a great impact on the lifetime. The reduction of TD is essential to increasing the carrier lifetime of the as-grown thick epilayer.

PACS: 71.20.Nr, 61.72.−y, 81.15.Gh DOI: 10.1088/0256-307X/35/7/077103

Silicon carbide (SiC) has become an important material for the development of high voltage power devices, which is beyond the theoretical limitations of Si-based power devices, owing to its superior properties such as wide band gap, high critical breakdown field, high thermal conductivity, and high saturation electron drift velocity.[1−3] However, in spite of the progress made in material growth and device fabrication, the material defects, such as basal plane dislocations, carrots, and triangle defects (TDs), are induced to the degradation of device performance and reliability. For high voltage unipolar switching devices, a problem of particular concern is the high forward-voltage drop dominated by a thick low-doped n-drift region, which results in excessive conduction losses. Ideally, a large amount of minority carriers injected into the drift region under forward bias in the high voltage bipolar device,[4,5] called conductivity modulation, will increase the electrical conductivity of the drift layer, and eventually minimize the forward voltage drop. The minority carrier concentration injected is directly limited by the carrier lifetime, which obviously affects the electrical properties of bipolar devices. Thus a long minority carrier is a particularly important parameter for bipolar structures. Recently $Z_{1/2}$ defects have been proposed as the limiting defects.[6−18] To eliminate the $Z_{1/2}$ center, C^+ implantation with subsequent Ar annealing[19,20] and thermal oxidation[21] have been proposed. In these methods, the generated excess carbon atoms are diffused into the epilayer, and carbon vacancy defects are filled with carbon atoms. Carrier lifetime control in n-type 4H-SiC epilayers can be achieved by low-energy electron irradiation.[22,23] Apart from the intrinsic defects which provide deep levels in the bandgap and act as effective traps or recombination centers for free carriers, structural defects may also influence the recombination.[24] Large area structural defects and dislocations have shown to significantly reduce the local carrier lifetime in Si.[25]

Imperfections in the crystal structure (such as dislocations, micropipes, in-grown stacking faults, and low angle grain boundaries), and surface morphological defects (such as TDs) should give rise to defect energy-levels in the band gap acting as nonradiative recombination centers and hence reduce the carrier lifetime. The length L of such surface defects along the $[11\bar{2}0]$ direction is almost followed by the equation $L = d/\tan\theta$ (d the film thickness, θ the off-cut angle). This relationship indicates that the thicker the epilayer is, the larger the size of those defects will be. Due to the particles falling down from up-wall of the chamber, the generation of TDs is a significant obstacle in the growth of thick 4H-SiC homoepitaxial layers. It is meaningful to study the relation between TDs and lifetime, while little in the literature has paid attention to the quantitative lifetime concerned with TDs in thick 4H-SiC epitaxial layers.

In this Letter, we investigate the effect of triangular defects on the carrier lifetime in a 180-μm-

*Supported by the National Key Research and Development Program of China under Grant No 2016YFB0400500.
**Corresponding author. Email: xytang@mail.xidian.edu.cn

thick as-grown 4H-SiC epilayer by means of microwave photoconductivity decay (μ-PCD) lifetime measurements and photoluminescence (PL) measurements. The crystallographic structure is analyzed by scanning electron microscopy (SEM) and scanning transmission electron microscopy (STEM).

The samples used in this study were 180-μm-thick epilayers with n-type doping concentration of $3.7 \times 10^{14}\,\mathrm{cm}^{-3}$ grown by a horizontal hot-wall CVD reactor. Commercial 4H-SiC wafers with 4° off-cut toward $[11\bar{2}0]$ were used as substrates. The growth of the epitaxial layer was performed with a hydrogen, trichlorosilane (TCS), and propane gas system. Nitrogen gas was used as an n-type dopant. The measurements of the carrier lifetime were performed by μ-PCD at room temperature. Free carriers were created by laser excitation using a diode-pumped frequency-tripled yttrium aluminum garnet laser with emission at 355 nm. PL measurements were carried out and compared with the lifetime images. The crystallographic structure, including polytype variations and defects, was studied using SEM and STEM.

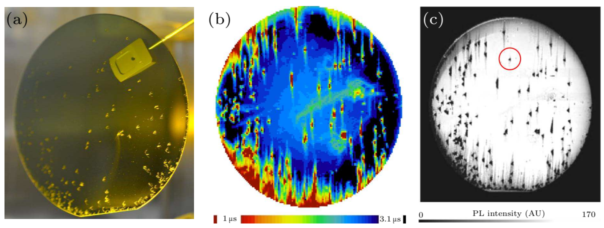

Fig. 1. (a) Image of triangular defects, (b) lifetime, and (c) PL mapping of 4H-SiC epitaxial wafer.

It is known that low off-axis (4° or less) epitaxial growth suffers from the formation of triangular defects, which are attributed to the larger terrace width resulting in two-dimensional nucleation.[1] Earlier studies of these features have been reported for layers grown by CVD.[26,27] Two kinds of planar triangular defects are observed in our study. One is with nothing in the source of the TD, and the other is with nucleation in the source. It is found that a tri-defect with nothing in the source is attributed to the different growth conditions between the buffer layer and the epilayer, while a tri-defect with nucleation in the head is due to the contamination of the substrate or the downfall during the growth progress. There have been some other reports about substrate defects serving as the origin of TDs. It has been suggested that TDs may also nucleate at silicon droplets falling on the surface.[28] Figure 1(a) displays an image of the TDs. Full wafer mapping of the carrier lifetime and PL has been performed as shown in Figs. 1(b) and 1(c). In this study, the lifetime values have been utilized for the following analysis. The average lifetime of as-grown 180-μm-thick wafer is 2.59 μs. An increase of the carrier lifetime is observed with increasing the thickness of the epilayer. It is suggested that the increase of the carrier lifetime observed in thicker epilayer was mostly due to the reduction of the influence on the carrier diffused into the lower quality substrate.

It is found that the lifetime is higher in the center area compared with the edge of the wafer. This could be related to the imperfect crystalline quality on the edge area of the wafer, which has high dislocation densities. In the defect-free regions, a higher carrier lifetime has been observed. It is also found that the carrier lifetime is dependent on the TDs, whose evidence is that the lifetime is lower near the TDs, while the reason is still unclear.

Figure 2 shows the μ-PCD decay curves measured on the defect-free (P1), side (P2), and surface (P3) of TDs on the 180-μm-thick epilayer. The decay curves exhibit an initially fast decay component and a subsequently slow decay component. The lifetime is 3.02 μs in the defect-free regions, which are 1.34 μs and 0.77 μs at the surface and side of TDs, respectively. The low minority carrier lifetime is measured around the defects. At the surface and side of TDs, the initial decay is fast and then becomes slow. The initial fast decay may be caused by the surface recombination, while the slower component can be influenced by the minority carriers trapped in the bulk. It is indicated that the recombination centers appeared at the TDs and nearby.

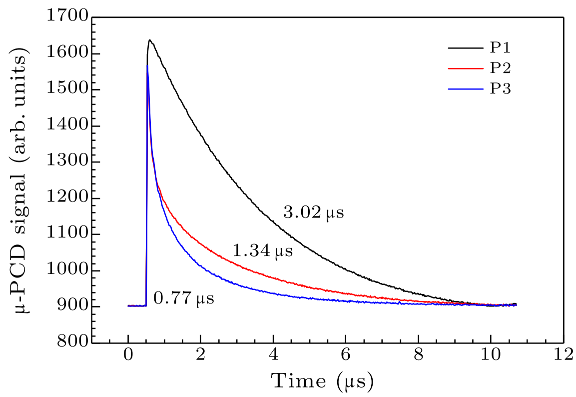

Fig. 2. The μ-PCD decay curves at room temperature obtained on a 180-μm-thick 4H-SiC epilayer. The decay curves for the free-defect point (P1), surface of TD (P3), and side of TD (P2).

To further investigate the origin of the lowering lifetime, the optical images and PL intensity mapping of the defects are shown in Fig. 3. The optical image in Fig. 3(a) is taken from the area marked in Fig. 1(c). Figures 3(b)–3(d) show the monochromatic PL intensity mapping at the wavelengths of 390 nm, 420 nm, and 540 nm, respectively. For the perfect 4H-SiC material, there is only one peak located at 390 nm with a tail at the low energy side,[29] which corresponds to the band edge emission of 4H-SiC. The area marked by P1 in Fig. 3(a) exhibits this peak, whose intensity of this area at 390 nm is strongest in Fig. 3(b).

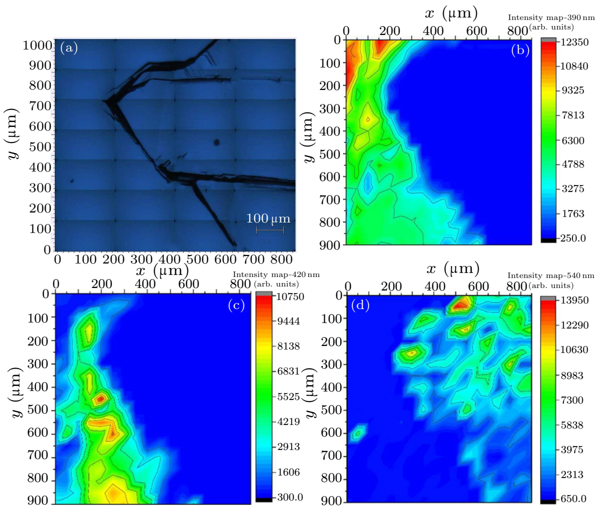

Fig. 3. (a) The optical image of defects, PL intensity mapping at (b) 390 nm, (c) 420 nm, and (d) 540 nm.

The area marked by P2 emits an additional luminescence at 420 nm besides the band-edge. Figure 3(c) shows the PL intensity mapping at 420 nm. Hoshino *et al.* believed that the emission around 420 nm was due to an in-grown type stacking fault (SF) related emission.[30] Odawara *et al.* found that the 540 nm peak in the PL spectrum originated from 3C-SiC.[31] From Fig. 3(d), it is found that the P3 area is 3C-SiC polytype, which is because of the triangular defects induced from 3C-SiC. In combination with the results of Fig. 2, the 3C-SiC polytype makes a great impact on the lifetime. Thus the reduction of TDs is essential to increasing the carrier lifetime of the thick epilayer.

It has been reported that the TDs are comprised of a stacking fault bound by partial dislocations propagating in the basal plane from the substrate through the epitaxial layer.[32,33] It is necessary to reduce the density of TDs for improving the lifetime of thick epitaxial layers. The structure of a triangular defect was examined by STEM, which directly shows the polytype of 3C-SiC inclusion and its morphology. From Fig. 4, it can be clearly observed that the structure of the 3C-SiC inclusion inside the triangular defect extends along the base plane direction, which is further confirmed by a high resolution image of the bright-field (BF)-STEM (Fig. 4(b)) and the high-angle annular dark-field (HAADF)-STEM image (Fig. 4(c)) of the interface between 3C-SiC and 4H-SiC. In Fig. 4(c), it is clearly shown that the fingerprint information is displayed for the lamellar 3C type inclusions.

The two-dimensional nucleation of epitaxial growth produces small cores for the 3C type, which blocks the step flow and extends along the base plane direction, eventually forming a triangular shape defect on the epitaxial surface. The two-dimensional nucleation can be suppressed by reducing the growth rate.

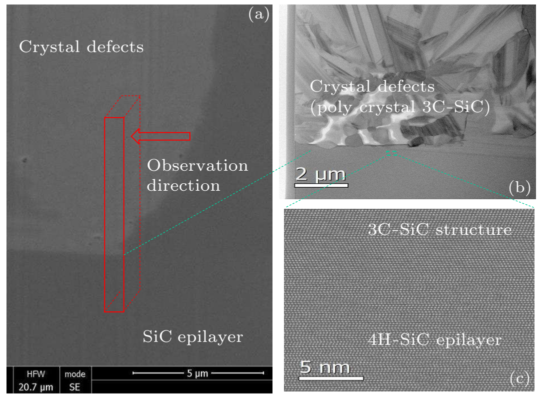

Fig. 4. SEM and STEM images of the triangular defect included in SiC epilayer. (a) SEM image of the triangular defect along the $[11\bar{2}0]$ direction, (b) BF-STEM image, and (c) HAADF-STEM image of defects at the interface between 3C-SiC and 4H-SiC.

In summary, the influence of TD on the carrier lifetime has been studied quantitatively in a 180-μm-thick 4H-SiC epilayer prepared by the CVD method. From the results of PL and μ-PCD measurements, it is found that the carrier lifetime near the TD is decreased obviously in comparison with that of a defect-free region, which is from 3.02 μs down to less than 1.34 μs. In addition, it is found that the carrier lifetime is higher on the side of the TD, which has increased by a factor of about 1.5 compared with that on the surface of the TD. This may be concerned with the 3C-SiC polytype at the surface of the TD since the carrier lifetime of 3C-SiC is lower than that of 4H-SiC. Combined with the analysis of STEM, the results also show that the carrier lifetime is affected by stacking faults around the triangle defect. Our study clarifies the quantitative impact of the TD structure on the carrier lifetime, which is meaningful for further investigation of SiC defects, as well as their effects on carrier lifetimes.

Detailed optical lifetime mapping of the 4H-SiC epitaxial layer shows large scale variations in full wafer mapping, which correlates with structural defects replicated from the substrate, such as polytype inclusions, grain boundaries, and basal plane slip bands. The mappings using high spatial resolution over selected regions may further reveal the influence of structural defects in the epitaxial layer. The identified defects which impact the carrier lifetime are the TDs, and different types of in-grown stacking faults.

It is demonstrated that carrier lifetime mapping measured by the μ-PCD method is a useful technique to characterize the epitaxial layers. The PL image of the epilayers is a useful technique for the detection of structural defects beneath the surface. Such defects could not be observed using the standard optical techniques. The correlation between the μ-PCD carrier lifetime mapping and PL mapping is quite helpful to identify the sources of reducing the carrier lifetime.

References

[1] Matsunami H and Kimoto T 1997 *J. Mater. Sci. Eng.* R **20** 125
[2] Dong L, Sun G S, Yu J et al 2013 *Chin. Phys. Lett.* **30** 096105
[3] Kimoto T 2015 *Jpn. J. Appl. Phys.* **54** 040103
[4] Van Brunt E, Cheng L, O'Loughlin M J et al 2015 *Mater. Sci. Forum* **821** 847
[5] Kaji N, Niwa H, Suda J et al 2015 *IEEE Trans. Electron Devices* **62** 374
[6] Zhang J, Storasta L, Bergman J P et al 2003 *J. Appl. Phys.* **934** 708
[7] Tawara T, Tsuchida H, Izumi S et al 2004 *Mater. Sci. Forum* **457** 565
[8] Kawahara K, Thang Trinh X, Tien Son N et al 2014 *J. Appl. Phys.* **115** 143705
[9] Ayedh H M, Nipoti R, Hallén A et al 2017 *J. Appl. Phys.* **122** 025701
[10] Kimoto T, Kawahara K, Zippelius B et al 2016 *Superlattices Microstruct.* **99** 151
[11] Klein P B, Shanabrook B V, Huh S W et al 2006 *Appl. Phys. Lett.* **88** 052110
[12] Son N T, Trinh X T, Løvlie L S et al 2012 *Phys. Rev. Lett.* **109** 187603
[13] Cheng P, Zhang Y M, Zhang Y M et al 2010 *Chin. Phys.* B **19** 097802
[14] Miyazawa T, Ito M and Tsuchida H 2010 *Appl. Phys. Lett.* **97** 202106
[15] Ichikawa S, Kawahara K, Suda J et al 2012 *Appl. Phys. Express* **5** 101301
[16] Zippelius B, Suda J and Kimoto T 2012 *J. Appl. Phys.* **111** 033515
[17] Ayedh H M, Bobal V, Nipoti R et al 2014 *J. Appl. Phys.* **115** 012005
[18] Kimoto T and Cooper J A 2014 *Fundamentals of Silicon Carbide Technology* (Singapore: Wiley)
[19] Storasta L and Tsuchida H 2007 *Appl. Phys. Lett.* **90** 062116
[20] Saito E, Suda J and Kimoto T 2016 *Appl. Phys. Express* **9** 061303
[21] Burk A A, Richmond J, Zhang J et al 2017 *Mater. Sci. Forum* **897** 587
[22] Danno K, Nakamura D and Kimoto T 2007 *Appl. Phys. Lett.* **90** 202109
[23] Kimoto T, Danno K and Suda J 2008 *Phys. Status Solidi* B **245** 1327
[24] Myers-Ward R L, Lew K K, VanMil B L et al 2008 *Mater. Sci. Forum* **600** 481
[25] Taishi T, Hoshikawa T, Yamatani M et al 2007 *J. Cryst. Growth* **306** 452
[26] Hallin C, Konstantinov A O and Pecz B 1997 *Diamond Relat. Mater.* **6** 1297
[27] Booker I D, Hassan J U, Lilja L et al 2014 *Cryst. Growth Des.* **14** 4104
[28] Miyanagi T and Nishino S 2002 *Mater. Sci. Forum* **389** 199
[29] Feng G, Suda J and Kimoto T 2009 *Appl. Phys. Express* **94** 091910
[30] Hoshino N, Tajima M, Nishiguchi T et al 2007 *Jpn. J. Appl. Phys.* **46** L973
[31] Odawara M, Koji K, Yoshihiko M et al 2014 *Mater. Sci. Forum* **778** 382
[32] Liu K, Stahlbush R, Twigg M E et al 2007 *J. Electron. Mater.* **36** 297
[33] Wu P, Emorhokpor E, Yoganathan M et al 2007 *Mater. Sci. Forum* **556** 247