Annex III
K. 15/424

Enhancing the performance of SiC power devices : a collaboration of Hong Kong academy and Mainland industry

LING Chi Chung Francis
Department of Physics/Faculty of Science

19/4/2024

Summary of the Impact

- Invented a new industrial fabrication procedure for the Al-implantation-annealing p-type dopant introduction process, which is an essential step for manufacturing SiC diode devices. This results in reducing the reverse biased leakage current by 30 times, which has significant technological and environmental impacts.
- Created significant economical impact. The Mainland industry partner Alpha Power Solutions (APS) adopted this procedure into their production line. 20M units of SiC diode has been manufactured, estimated to have market value >HKD1B.
- Offers channel for Mainland-industry-HK researchers exchange, fostering HK to better integrate into the overall development of the country and bringing social impact.

Underpinning Research

- Outline

1. Results of the Research Works

- Study the thermal evolution of carbon vacancy in Al-implanted SiC p-n junction diode. Disclosed the importance of thermal equilibrium creation of carbon vacancy at annealing temperature >1800 ^{o}C. [Ayedh et al, J. Phys. D 54: 455106 (2021)].
- Observed the correlation between carbon vacancy and the reverse biased leakage current of APS commercial SiC diodes. Unambiguously identified the dominant mechanism for leakage current transport as the Poole-Frenkel emission from the carbon vacancy to the conduction band. Implying that suppressing the carbon vacancy would suppress the leakage current [Ho et al, Semicond. Sci. Technol. 38: 115007 (2023)].
- Collaborating with APS, develop an industry compatible Al-implantation-annealing process for p-type doping, which compromises a lower annealing temperature (1700 ^{O}C) for adequate Al thermal dopant activation and acceptably thermal equilibrium carbon vacancy creation. Comparing to the conventional industry process usually involving annealing temperature >1800 ^{o}C, this new process yielded devices with carbon vacancy concentration reduced from 10^{15} cm^{-3} to <10^{11} cm^{-3}; and leakage current suppressed by over 30 times [Lin et al, IEEE Electron Device Letters 44: 578 (2023)].

Underpinning Research

2. Role of Research Works

- [Ayedh et al, J. Phys. D 54: 455106 (2021)]

Collaborated with the SiC group of Oslo University (OS), this project revealed the physics of thermal evolution of carbon vacancy in Al-implanted SiC. The concept of the project was conceived by the OS and HKU groups. The laboratory prototype samples was fabricated by OU and the carbon vacancy was characterized by HKU.

- [Ho et al, Semicond. Sci. Technol. 38: 115007 (2023)] and [Lin et al, IEEE Electron Device Letters 44: 578 (2023)]

Collaborated with the Alpha Power Solutions (APS), HKU steered the project, conceived the project concept, characterized the carbon vacancy, studied the leakage current transport mechanism, performed data analysis and modeling. APS supplied the commercial diode samples and fabricated tailored-made industrial compatible samples with the HKU guidance using their industrial fabrication line.

Underpinning Research

3. Key contextual information

- These research work is under the context of the project ‘Developing and commercializing the SiC power devices and modules for the electrical vehicle (EV) applications’ supported by the Key-Area Research and Development Program of Guangdong Province (No. 2020B10170002, started and ended in 01/2020 and 12/2022 respectively; then extended to 12/2023 because of the delay in progress by the COVID). Comprising of Mainland and Hong Kong industries and universities, this project is leaded by 深圳英飞源技术有限公司 (Infypower Shengzen), and co-investigated by Alpha Power Solutions (APS), 天域半導体科技有限公司 (Tianyu), Fudan University, Guangdong University of Technology and HKU. The three companies are at the different positions of the whole industrial chain of EV power device manufacturing, in which Tianyu supplies SiC epi wafers as the raw material to APS for the production of SiC power devices. APS supplies the SiC power devices to Infypower for the production of modules used in EV. We collaborate with APS for developing and improving their SiC devices. The total budget of the project is RMB 16M from the Guangdong Province Government and RMB 40M matching from the three companies. We share the budget of RBM0.8M (HKD0.936M) delivered to HKU from the Guangdong Government grant, and in extra with all the sample fabrication cost supported by APS. The project was also supported by a ITF grant of HKD0.8855M plus 2 posdoc supported by the corresponding Talent Hub grant (>HKD1.5M approved); and a research contract from APS (HKD0.15M).

Underpinning Research

4. **Innovativeness** of the knowledge arising from your research at HKU

- In the SiC device field of industry, post-Al-implantation annealing is usually done at temperature >1800^{o}C. The high temperature is for maximizing the dopant activation and annealing out the atomic scale defects introduced by the implantation.
- Our innovativeness of the knowledge includes:

(i) Annealing at temperature >1800 ^{o}C cannot thermally remove atomic scale defects completely, but create carbon vacancy via thermal equilibrium generation.

(ii) The reversed biased current is usually thought to be associated with tunneling current. However with concrete evidence, we found that the leakage current is dominantly originated from the Poole-Frenkel emission from the carbon vacancy.

(iii) We developed a new process to activate the Al dopant and remove the implantation-induced defects. We found that the implantation-induced defects causing device performance degradation converted to carbon vacancy at temperatures >1200 ^{o}C. Thus, removing carbon vacancy is the essential for enhancing device performance. This new process includes a lower annealing temperature (1700 ^{o}C) and longer period of annealing time for sufficient dopant activation and removing implantation-induced defects. We also pioneered an extra process of depositing a sacrifice oxide layer, for which C interstitials is created upon the formation of SiO_2. These carbon interstitials diffuse into the SiC body and fill the carbon vacancy, thus eliminating the carbon vacancy and improving the device performance by reducing the leakage current by over 30 times.

Underpinning Research

5. Significance of the key insights or findings from the research that relate to the impact achieved by the KE project

- The SiC industry usually pay attention to control the micron scale defects observable by scanning electron microscope, but pay very little attention to atomic scale defects as atomic scale defects are very difficult to be characterized and control. However, atomic scale defects in semiconductor is crucial for determining the performance of devices. The PI of the project is an expert in atomic scale defect characterization and control with over 30 years of experience. This project focus on the control of atomic scale defects in SiC devices for enhancing the device performance.

- p-type doping by Al implantation is an essential step for fabricating diodes. The current research findings enable the improvement of step in the mass production line of SiC devices. Based on the key insights and findings of the research, the company APS developed a new Al-implantation-annealing process in their production line for introducing Al dopant with advise and guidance given by HKU.

Knowledge to be Exchanged

- Please elaborate the "knowledge to be exchanged" in your project, and how it relates to the broader goals of promoting innovation, economic, cultural &/or social impact.

1. What specific knowledge is being exchanged in your project?

(i) Thermal evolution of carbon vacancy in Al-implanted SiC

(ii) Reverse biased leakage current is not associated with tunnelling current, but dominated by the Poole-Frenkel current with emission from carbon vacancy.

(iii) Annealing with lower temperature and longer period can already sufficiently activate the Al dopant and remove defects.

(iv) Use of sacrifice oxide to remove carbon vacancy.

(v) A new industry compatible annealing process for Al activation and eliminating carbon vacancy, suppressing leakage current by over 30 times.

2. How is the knowledge that is exchanged in your project generated, curated, and disseminated? And how it is used to drive innovation, economic development, and/or social change?

The knowledge was generated by the research collaboration with the SiC group of Oslo University and the APS (details given in 2. Role of Research Works). Three papers are published:

'Carbon vacancy control in p^+-n silicon carbide diodes for high voltage bipolar applications', H. M. Ayedh*, K-E. Kvamsdal, V. Bobal, A. Hallén, F.C.C. Ling, and A. Yu. Kuznetsov, J. Phys. D: Appl. Phys. **54**, 455106 (2021). Available at: https://doi.org/10.1088/1361-6463/ac19df

'Suppression of the carbon vacancy traps and the corresponding leakage current reduction in 4H-SiC diodes by low-temperature implant activation in combination with oxidation', Tianxiang Lin, Lok-Ping Ho, Andrej Kuznetsov, Ho Nam Lee, Tony Chau, Francis Chi-Chung Ling*, IEEE Electron Device Lett. 44, 578 (2023). https://doi.org/10.1109/LED.2023.3242296

'Correlations between reverse biased leakage current, cathodoluminescence intensity and carbon vacancy observed in 4H-SiC junction barrier Schottky diode', Lok Ping Ho, Sihua Li, Tianxiang Lin, Jack Cheung, Tony Chau, Francis CC Ling*, Semicond. Sci. Technol. 38, 115007 (2023). https://iopscience.iop.org/article/10.1088/1361-6641/acfb32/meta

* Contact author

These research results reveals the fundamental physics of the thermal effects on atomic defects evolution, transport mechanism of leakage current and removal of carbon vacancy by sacrificial oxide during annealing. Leading to the conclusion that the conventional process used by the industry can be improved. The innovation and technical impact was derived from the understanding of the fundamental physics. The new process used in the mass production line was then developed by APS with the guidance on the physics concept by the HKU. The new commercial devices has significant performance improved and thus received good response from the market. A letter from the APS in Oct 2023 stated that 20M units of the devices have already been produced, estimated to have market cost >HKD 1B.
The physics knowledge published is universal and can also be the foundation for improving other SiC devices of other companies.

Any particular insights or ideas being shared from your project, and how are they being applied in practice?

- Technical staffs of semiconductor device industry usually receive engineering training and thus not familiarized with the fundamental physics mechanisms behind their manufacturing processes. There is thus room for material physicist to understand the fundamental physics behind the manufacturing processes, and find the breakthrough point for device performance improvement.
- It is very difficult for university research group to work on commercial device research alone because neither the university nor Hong Kong have the fabrication line (costing over HKD 1B); and the fabrication of a single batch of industry compatible sample with a set of growth parameters cost over HKD 50k.

Engagement

1. Engagement process for HKU to transfer the knowledge to the target beneficiaries

- During the development of the new process for mass production, HKU suggested 2 points to be modified, namely the lower temperature and longer annealing period; and the introduction of the sacrifice oxide for removing carbon vacancy.
- Samples with different annealing conditions recommended by HKU were produced with the mass production line by APS. All the samples were then studied by HKU by deep level transient spectroscopy for characterizing the carbon vacancy. The annealing conditions were tuned for minimum carbon vacancy concentration and leakage current.

Engagement

2. **External partners**, if any

- Prof Andrej Kuznetsov, Oslo Univeristy
- Tony Chau, CEO, Alpha Power Solutions

Engagement

3. **Innovativeness** of the engagement approach

Conventionally, the SiC industry used a very high temperature for the post Al-implantation annealing. The temperature used is usually above 1800 ^{o}C and the APS used a temperature of 1950 ^{o}C. It is commonly believed that high temperature is good for maximizing the Al-dopant activation and reducing atomic scale defects created by Al implantation. However with this high temperature treatment, it is well known that carbon vacancy cannot be removed.

Our research showed that (i) All other electrical active defects like silicon vacancy converted to carbon vacancy at 1200 ^{o}C; (ii) Equilibrium thermal creation of carbon vacancy becomes significant at temperature above 1800 ^{o}C; (iii) Introduction of sacrifice oxide suppressed the carbon vacancy concentration; (iv) Reverse biased leakage current has the origin of Poole Frenkel emission from the carbon vacancy, reducing carbon vacancy decreases leakage current.

The newly developed procedure used in the mass production of SiC devices by APS is based on our research findings. Using a lower annealing temperature and longer annealing time for dopant activation is an innovative concept and approach to the SiC industry. Sacrifice oxide is usually used in the SiC industry to smoothen the SiC surface but no one uses it to suppress carbon vacancy. The leakage current is usually thought to be associated to the tunneling, but we give concrete direct evidence it is associated to Poole Frenkel emission from the carbon vacancy to the conduction band.

Impacts Achieved

1. **Beneficiaries** - the non-academic sector(s) or organizations that have benefitted or been impacted on

- APS benefited from having a new Al-implantation-annealing process which yields SiC devices with lower leakage current. 20M units of the devices have already been manufactured, with estimated market cost >HKD 1B.
- The technical staff of APS gain new insight into SiC device design.
- This also benefits the green environment as devices with lower leakage current have higher energy efficiency. For the same voltage, the power loss is proportional to the leakage current, i.e. a reduction of >30 times of energy save.
- The whole SiC industry also benefit from the knowledge we gain and publish in journals. These knowledge can be the fundamental new concepts for developing future SiC devices.

Impacts Achieved

2. **Nature and extent of the impact** – the outcomes of the engagement described above, e.g. how and when the beneficiaries have benefitted from your KE project, what had been changed or improved, and whether the impact still exists at present

- The APS has already used the new process for their SiC diode mass production. The process is still a current routine for their SiC diode manufacturing.
- We are now working in a new project to improve the performance of SiC MOSFET of APS. The new annealing process will also be used in this MOSFET development.
- With these knowledge and process as foundation, we are also working together with the Huairou National Laboratory, Beijing for developing next generation SiC devices.
- The whole SiC industry also benefit from the knowledge we gain and publish in journals. These knowledge can be the fundamental new concepts for developing future SiC devices.

Impacts Achieved

3. Description of the **evidence** or indicators of the extent of the impact (focus on the **evidence of the changes or improvement made** after the engagement activities)

An appreciation letter was sent by APS to thank for our contribution towards the development of their new manufacturing process. Also stated that 20 M units of SiC devices have already been produced.