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Development of 8-inch Key Processes for Insulated-Gate Bipolar Transistor

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ABSTRACT Based on the construction of the 8-inch fabrication line, advanced process technology of 8-inch wafer, as well as the fourth-generation high-voltage double-diffused metal-oxide semiconductor (DMOS+) insulated-gate bipolar transistor (IGBT) technology and the fifth-generation trench gate IGBT technology, have been developed, realizing a great-leap forward technological development for the manufacturing of high-voltage IGBT from 6-inch to 8-inch. The 1600 A/1.7 kV and 1500 A/3.3 kV IGBT modules have been successfully fabricated, qualified, and applied in rail transportation traction system.

KEYWORDS insulated-gate bipolar transistor (IGBT), high power density, trench gate, 8-inch, rail transportation

1 Introduction

Since the 1950s, the semiconductor industry has made great progress in both integrated circuit (IC)-based microelectronics and power semiconductor devices [1]. In the application, microelectronics act as the brain to control huge information flows while power semiconductor devices act as the heart to manage intensive energy flows. Their effective cooperation allows high efficiency energy utilization. With rapid development and maturity of both semiconductor materials and microelectronics process technologies, the third-generation power chips, represented by insulated-gate bipolar transistor (IGBT), has opened up a new area in the power semiconductor field [2].

The IGBT has become a popular choice of power semiconductor device for a wide range of industrial power-conversion applications due to technological advancement such as rugged switching characteristics, low losses, and simple gate drives. As an advanced power semiconductor device, the IGBT with high power capacity has been widely applied in most strategic emerging industries such as high speed rail transportation, electric vehicles, smart grid, and renewable energy [3–7]. The IGBT chip and its related technology has been monopolized by several giant companies possessing competitive technologies and applications for a long time, thus more than 95% IGBT products had to be imported. The situation can be attributed to two reasons. Firstly, the IGBT business chain is imperfect in China, and due to the fact that little attention was paid to the importance of IGBT technology in the earlier 1980s, domestic IGBT companies are normally 20–30 years younger than other major IGBT players. Secondly, the academic investigation and innovation on IGBT technology in China is lagging behind that of the advanced international institute, which results in poor intellectual property accumulation on IGBT chip design and process.

The development trends and key characteristics of IGBT chip technology were summarized in this paper. Besides, the new 8-inch fabrication line dedicated to IGBT in China Railway Rolling Stock Corporation (CRRC) Zhuzhou Electric Locomotive Institute Co., Ltd. was introduced, and the advanced IGBT processes and key technologies were also highlighted. Finally, the high power density IGBT modules with 1.7 kV and 3.3 kV IGBT and fast recovery diode (FRD) chipsets based on the new-generation 8-inch fabrication line were fabricated, qualified, and successfully applied in rail transportation traction system.

2 Development of IGBT technology

With regard to the device basic structure, an IGBT is a kind of compound power semiconductor device combined with a bipolar junction transistor (BJT) and a metal-oxide-semiconductor field effect transistor (MOSFET). An N-channel IGBT is basically a vertical power MOSFET constructed on a layer doped by *p*-type impurity, as illustrated in Figure 1 [8, 9]. Once a positive voltage is applied from the gate to the emitter, inversion electrons are generated underneath the gate in the P-base region. If the gate-emitter voltage is above the threshold voltage, enough electrons are generated to form a conductive channel across the body region, supplying a base current

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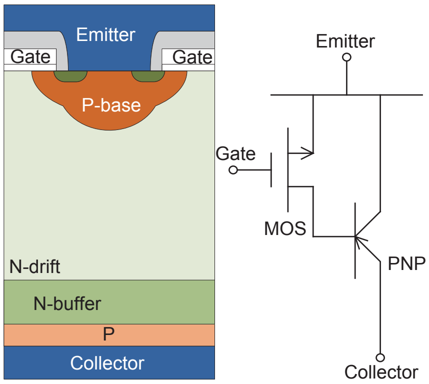

Figure 1. IGBT cross-section and equivalent circuit.

for the positive-negative-positive (PNP) transistor and allowing current to flow from the collector to the emitter. With the combination of an easily driven metal-oxide-semiconductor (MOS) gate and low conduction loss, IGBTs quickly replaced power bipolar transistors as the device of choice for high-current and high-voltage applications.

Basically, the performance of IGBT device is judged by static characteristics, dynamic characteristics, and reliability. The static characteristics consist of on-state voltage drop, gate threshold voltage, forward blocking voltage, and leakage current. The dynamic characteristics include switching losses and switching times, which are related to the dynamic losses and operation frequency. Finally, the reliability is mainly comprised of the reverse bias safe operating area (RBSOA) and the short circuit safe operating area (SCSOA). Normally, IGBTs have a significantly lower on-state voltage drop compared to that of unipolar devices in medium and high power classes. However, this is at the expense of increased turn-off time and loss. Besides, high current density and fast turn off speed prone to inducing narrow RBSOA and SCSOA. The ways to balance the trade-off among on-state voltage, turn-off energy and safe operating area (SOA) can be summarized as follows: refining fine pattern cell structure at the emitter side and tailoring the hole injection efficiency at the collector side, both are fully developed within the process evolvement of IGBT.

Figure 2 shows the key technologies during the development of IGBT technology since its invention. As we can see, the technologies on both sides of emitter and collector developed alternately and coordinately. At the early age, the collector region employed punch-through (PT) structure based on epitaxial wafer, while the cell on the emitter side used planar gate technology with large critical dimension. This kind of IGBT had poor anti-latch-up ability, high conduction voltage drop, and high turn-off energy. Besides, utilization of epitaxial wafer in PT-IGBT not only resulted in high cost of silicon material but also restricted its highest blocking voltage to be below 2 kV. The lately appeared non punch-through (NPT)-IGBT solved these problem by employing float-zone (FZ) wafer, laying the foundations for forwarding the IGBT to high-voltage field and reducing the cost significantly. Comparing with PT-IGBT, NPT-IGBT has dramatically reduced tail time owing to its lower injection efficiency of collector. In the meantime, improvement of refining cell pattern of planar IGBT and employing trench gate structure were realized on the emitter side for lower on-state voltage drop and more extensive SOA [10].

However, since the drift region of the NPT-IGBT was too wide, the reduction of the on-state voltage and turn-off loss was constrained. Aiming to solve this problem, the laser annealing and thin wafer processing technologies were introduced into the formation of field stop (FS) structure around the year of 2000, meanwhile the trench process based on advanced plasma etch technology was introduced on the emitter side [11, 12]. These two improvements not only significantly cut down the on-state voltage drop and turn-off losses, but also effectively improved the safe operation performance. In recent years, several new technologies were promoted to further improve the performance of the FS-IGBT. On the emitter side, the electron injection enhancement technology represented by the carrier storage technology significantly reduces the conduction voltage drop [13]. While on the collector side, the multi buffer structure and variable doping structure were developed to further optimize the injection efficiency of the collector [14]. In the future the trench gate technology will further develop toward the medium and high-voltage field and extend the boundary of power density of IGBTs [15, 16]. On the collector side, backside aligning and implantation will be introduced to further optimize the collector structure or integrate the free-wheeling diode on the backside [17, 18]. As is shown,

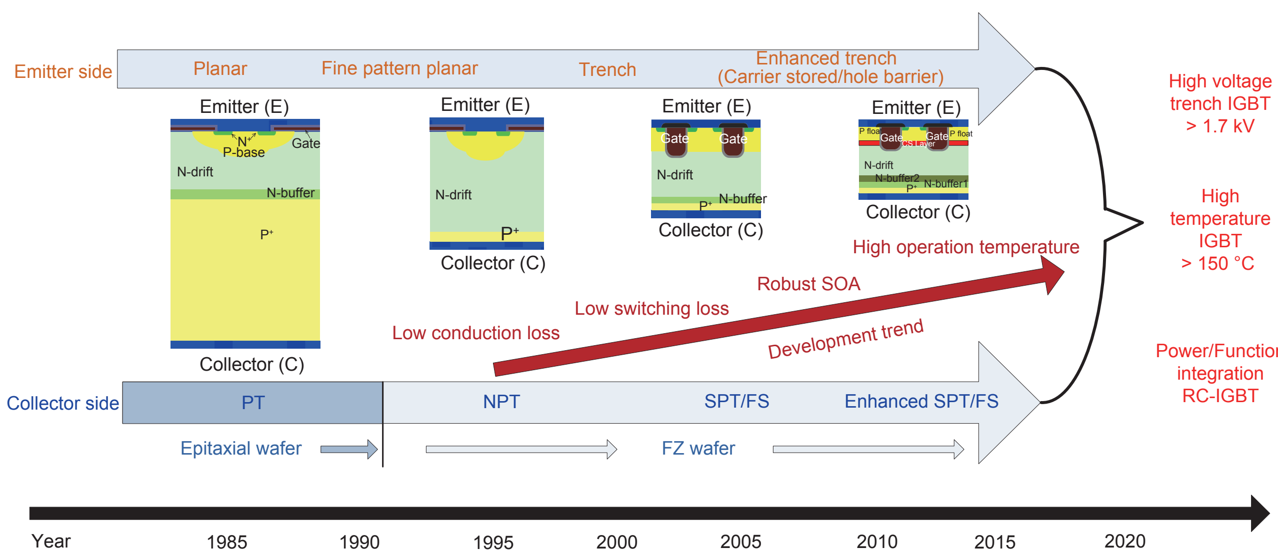

Figure 2. IGBT technology history and its trends.