

**Invited****Breakthrough in Semiconducting SiC towards Solid State Devices**

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Breakthroughs in crystal growth of semiconducting SiC which have triggered recent attention to this material are introduced. Growth of cubic SiC on Si, typical success in heteroepitaxial growth with a large lattice mismatch, is reviewed. Step-controlled epitaxy, which the author's group named and will be a key technology for future development of SiC solid state devices, is described in detail. Current status and future directions of SiC devices are presented.

**1. INTRODUCTION**

Silicon carbide(SiC) has refractory, radiation-resistant, mechanically hard and chemically inactive properties together with wide bandgap. Strong desire has been given for developing solid state devices, e.g. blue light-emitting diodes(LEDs) and transistors/ICs for high-temperature/harsh environments. The material is ordinarily produced by the Acheson method above 2500°C using silica and coke, which inevitably brings about the problem of purity for semiconductor use. Through many efforts, high-purity single crystals are grown using sublimation(Lely method). Rectifiers, particle detectors, tunnel diodes and LEDs have been fabricated to demonstrate the superiority of this material [1,2]. However, difficulties in processing technology have prevented the development of SiC solid state devices.

Recent progress in epitaxial growth of SiC at lower temperatures has given superior single crystalline layers and easy control of in-situ impurity doping[3,4]. Breakthrough is now appearing in SiC processing technology. In this report, brief summary of attractive properties of SiC and recent progress in epitaxial growth of SiC single crystals, mainly heteroepitaxy and homoepitaxy(step-controlled epitaxy), are presented. Current status of solid state devices and future expectation for SiC are discussed.

**2. ATTRACTIVE PROPERTIES OF SiC**

Among a number of polytypes (different crystal structures), 3C-SiC and 6H-SiC are practically interesting. The first number in

the expression shows the periodicity of stacking sequence, and the second character indicates crystal symmetry, such as cubic(C) or hexagonal(H). The energy gap of 3C-SiC and 6H-SiC is 2.20 and 2.86eV, respectively. The most noticeable is  $2 \times 10^7$  cm/s for saturation drift velocity of electrons above  $2 \times 10^5$  V/cm in 6H-SiC[5], together with high breakdown electric field of  $(2-3.7) \times 10^6$  V/cm[6]. The saturation electron drift velocity in 3C-SiC is estimated to be  $2.7 \times 10^7$  cm/s[7]. The electron mobility of  $1000 \text{ cm}^2/\text{Vs}$ [8] in 3C-SiC at low electric field is remarkably large for a wide gap semiconductor of 2.20eV.

**3. PROGRESS IN EPITAXIAL GROWTH****3.1 Heteroepitaxial growth of 3C-SiC on Si**

Since single crystals of 3C-SiC produced by sublimation methods are small, heteroepitaxial growth on Si has been studied extensively using vapor phase epitaxy(VPE). However, reproducible growth has been difficult, which is caused by the growth at high temperatures and large lattice mismatch of 20% between 3C-SiC and Si ( $a_{\text{SiC}}=0.4358 \text{ nm}$ ,  $a_{\text{Si}}=0.5430 \text{ nm}$ ). One of the approaches to overcoming this difficulty is to put a very thin layer of 3C-SiC prepared by carbonization (flowing hydrocarbon over Si substrates at around 1360°C) before CVD[3,4], which was proposed by the author's group.

Heteroepitaxial growth of 3C-SiC consists of etching, carbonization and CVD. A Si substrate is etched at 1180°C using a HCl flow with  $\text{H}_2$  carrier gas. Then, in a flow of  $\text{C}_2\text{H}_8$  the substrate is heated up to 1360°C in short time for carbonization. Immediately after, CVD growth of 3C-SiC is carried out

with  $\text{SiH}_4$  and  $\text{C}_3\text{H}_8$  at around  $1300^\circ\text{C}$ . The growth rate of 3C-SiC at  $1300^\circ\text{C}$  is about  $1.8\mu\text{m/h}$ [9]. At present, the diameter of single crystalline 3C-SiC is about 50-75mm.

Control of conduction type(n- or p-type) and carrier concentration is possible by in-situ doping. Electron mobilities of the grown layers are shown in Fig.1[10]. Single crystals on Si(100) can be used for device application. However, antiphase domain(APDs) exist owing to the growth of polar crystals on nonpolar substrates[11]. APD-free growth was proposed and realized by using a Si(100) wafer tilted towards [011][12].

### 3.2 Homoepitaxial growth of 6H-SiC (Step-controlled epitaxy)

The most remarkable progress in homoepitaxial growth is step-controlled epitaxy proposed by us[13,14]. Single crystals of 6H-SiC can be grown on angle-lapped 6H-SiC {0001} at  $1300\text{-}1500^\circ\text{C}$ , which is more than  $300^\circ\text{C}$  lower compared to ordinary growth temperatures. The density of surface steps is increased by angle lapping. Utilizing step-flow growth(lateral growth from the steps), single crystalline 6H-SiC with a very smooth surface is grown at lower temperatures. On a well-oriented (or natural) {0001} faces, twin crystalline 3C-SiC with double positioning boundaries is grown. Hereby, we named "step-controlled epitaxy", in which the polytype-controlled epitaxial growth at low temperatures can be realized by the aid of a number of steps[14,15].

Schottky barrier and pn junction diodes prepared by step-controlled epitaxy show excellent current-voltage characteristics owing to the smooth surface of the grown layer[16]. The breakdown voltage exceeds 100V, and it is increased to more than several hundred volts by optimizing junction profile. The breakdown electric field was calculated to be  $2.4 \times 10^6 \text{V/cm}$ .

## 4. CURRENT STATUS OF SiC DEVICES

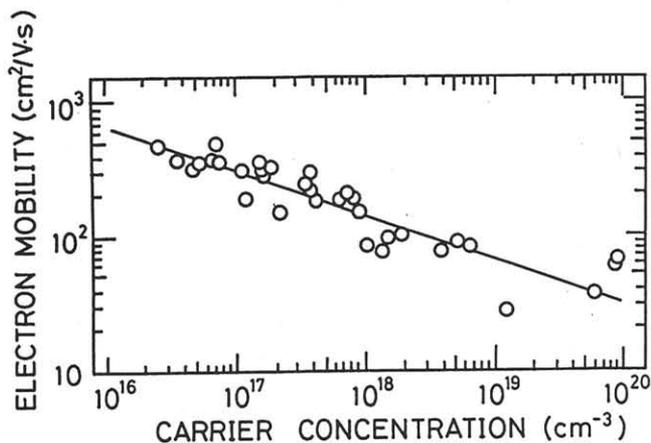


Fig.1 Electron mobilities of 3C-SiC on Si.

### 4.1 Blue light-emitting diodes

Blue LEDs of 6H-SiC pn junction are prepared using liquid phase epitaxy(LPE) with a Si melt in a graphite crucible. Since SiC has indirect band structure, effective centers such as donor-acceptor pairs should be utilized. The author's group proposed a dipping method to develop a convenient fabrication technique for blue LEDs[17,18]. Abrupt pn junctions were prepared using a rotation dipping technique[19].

The light-emission mechanism was investigated through the detailed analysis of temperature and excitation dependence of the spectra and time-resolved spectral change. The main mechanism is attributed to recombinations of (i)donor-acceptor (D-A) pairs ( $\sim 480\text{nm}$ ), (ii) excitons bound at localized centers related to Al impurities ( $\sim 455\text{nm}$ ), and (iii)free excitons ( $\sim 425\text{nm}$ ) [19].

The external quantum efficiency of SiC blue LEDs prepared by LPE is approaching to  $2 \times 10^{-2}\%$  (7mcd for 20mA in  $250 \times 250 \mu\text{m}^2$ )[20]. The brightness exceeds over 20mcd for 20mA at present time. After the success in step-controlled epitaxy in VPE, pn junctions showing blue light emission can be prepared[16].

### 4.2 Transistors

Inversion-mode MOSFETs (metal-oxide-semiconductor field effect transistors) using APD-free 3C-SiC on Si(100)  $2^\circ$ -off towards [011] was fabricated by the author's group for the first time[21]. Source and drain regions were prepared by ion implantation of  $\text{P}^+$ -ion, and a gate insulator by thermal oxidation. The structure of the MOSFET and current-voltage characteristics at room temperature are shown in Fig 2 for a channel of  $20\mu\text{m}$  in length and  $500\mu\text{m}$  in width. The threshold voltage was 2.80V, and the effective mobility of electrons in the channel was estimated to be about  $100\text{cm}^2/\text{Vs}$ . Similar characteristics at room temperature and operation at 573K were reported with a gate length of  $5\mu\text{m}$ [22]. The maximum transconductance was  $0.46\text{mS/mm}$  at room temperature. Higher transconductance was obtained for a  $3.5\mu\text{m}$ -gate device, which operated even at 673K. Some of the devices operated at 823K.

Depletion-mode MOSFETs were fabricated using 3C-SiC grown on well-oriented 6H-SiC[22].The structure and current-voltage characteristics are shown in Fig.3. The maximum transconductance at room temperature was  $5.32\text{mS/mm}$  for a gate length of  $7.2\mu\text{m}$ . This device operated even at 923K. When the gate length was reduced to  $2.4\mu\text{m}$ , the maximum transconductance was increased to  $9.79\text{mS/mm}$  at room temperature.

## 5. FUTURE OF SiC

For realizing SiC devices, ingots of SiC with large diameter is produced by a

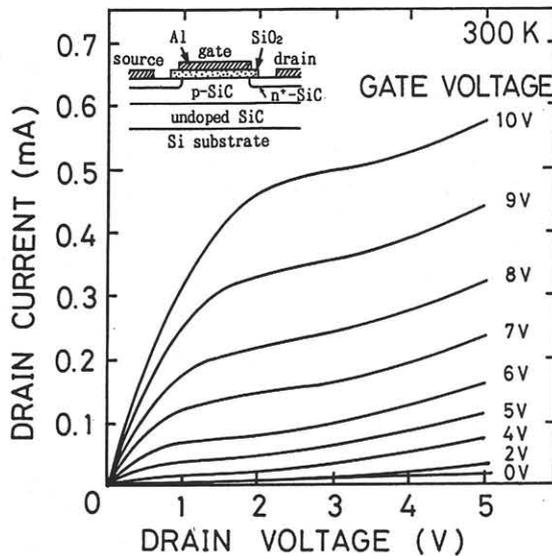


Fig.2 Inversion-mode MOSFET of 3C-SiC on Si.

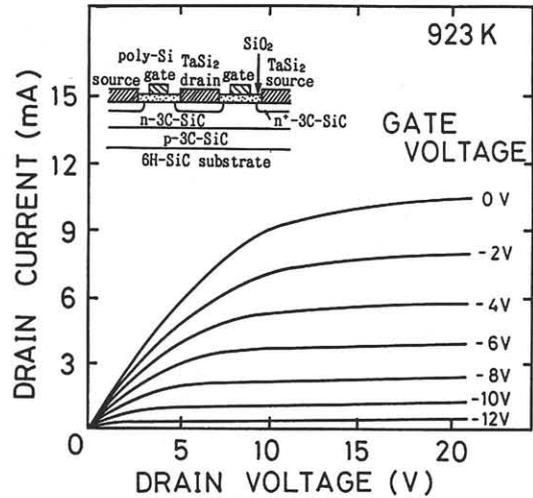


Fig.3 Depletion-mode MOSFET of 3C-SiC on 6H-SiC.

modified Lely method (sublimation onto a SiC seed), using a concentric dual-cylinder furnace of graphite[20]. The maximum diameter of ingots nowadays is around 30mm. Sublimation growth onto a 3C-SiC seed prepared on Si is hopeful. When the furnace temperature was kept higher than 2200°C, 6H-SiC(0114) single crystals can be grown on 3C-SiC(100)[23].

Silicon carbide has been examined from the perspective of physical limits on semiconductor devices by introducing figures of merit[24]. The principal advantage of SiC for solid state devices is its high breakdown voltage and high thermal conductivity. Very recently, some materials were examined by using new figures of merit for the use of power devices[25]. Here again, SiC is chosen as a good candidate.

#### REFERENCES

- 1) R.B.Campbell and H.C.Chang, *Semiconductors and Semimetals* 7 (Academic Press, 1971) p.625.
- 2) E.Pettenpaul, W.von Muench and G.Ziegler, *Inst. Phys. Conf. Ser. No.53* (The Inst. Physics, 1980) p.21.
- 3) H.Matsunami, *Thin Films from Free Atoms and Particles* (Academic Press, 1985) p.301.
- 4) H.Matsunami, *Optoelectronics-Devices and Technologies*, 2 (1987) 29.
- 5) W.von Muench and E.Pettenpaul, *J. Appl. Phys.*, 48 (1977) 4823.
- 6) W.von Muench and I.Pfaffeneder, *J. Appl. Phys.*, 48 (1977) 4831.
- 7) D.K.Ferry, *Phys. Rev.B*, 12 (1975) 2361.
- 8) W.E.Nelson, F.A.Halden and A.Rosengreen, *J. Appl. Phys.*, 37 (1966) 333.
- 9) S.Nishino, H.Suhara, H.Ono and H.Matsunami, *J. Appl. Phys.*, 61 (1987) 4889.
- 10) K.Shibahara, T.Takeuchi, S.Nishino and H.Matsunami, *Jpn. J. Appl. Phys.*, 28 (1989) 1341.
- 11) K.Shibahara, S.Nishino and H.Matsunami, *J. Crystal Growth*, 78 (1986) 538.
- 12) K.Shibahara, S.Nishino and H.Matsunami, *Appl. Phys. Lett.*, 50 (1987) 1888.
- 13) N.Kuroda, K.Shibahara, W.S.Yoo, S.Nishino and H.Matsunami, *Ext. Abstr. 19th Conf. Solid State Devices and Materials* (Tokyo, 1987) p.227.
- 14) H.Matsunami, T.Ueda and H.Nishino, *Proc. Mat. Res. Soc. Symposium* 162 (1990) 397.
- 15) H.S.Kong, J.T.Glass and R.F.Davis, *J. Appl. Phys.*, 64 (1988) 2672.
- 16) K.Shibahara, N.Kuroda, S.Nishino and H.Matsunami, *Jpn. J. Appl. Phys.*, 26 (1987) L1815.
- 17) A.Suzuki, M.Ikeda, N.Nagao, H.Matsunami and T.Tanaka, *J. Appl. Phys.*, 47 (1976) 4546.
- 18) H.Matsunami, M.Ikeda, A.Suzuki and T.Tanaka, *IEEE Trans. Electron Devices*, ED-24 (1977) 958.
- 19) M.Ikeda, T.Hayakawa, S.Yamagiwa, H.Matsunami and T.Tanaka, *J. Appl. Phys.*, 50 (1979) 8215.
- 20) G.Ziegler, P.Lainig, D.Theis and C.Weyrich, *IEEE Trans. Electron Devices*, ED-30 (1983) 277.
- 21) K.Shibahara, T.Saito, S.Nishino and H.Matsunami, *IEEE Electron Device Lett.*, EDL-7 (1986) 692.
- 22) J.W.Palmour, H.S.Kong and R.F.Davis, *J. Appl. Phys.*, 64 (1988) 2168.
- 23) W.S.Yoo, S.Nishino and H.Matsunami, *J. Crystal Growth* 99 (1990) 278.
- 24) R.W.Keyes, *Silicon Carbide-1973* (University of South Carolina Press, 1974) p.534.
- 25) B.J.Baliga, *IEEE Electron Device Lett.*, 10 (1989) 455.