Silicon Carbide Power Device Projects

In the field of green technology, which works to reduce the burden on the environment, power semiconductor devices are currently drawing attention. In the article below, SAMCO provides an introduction to the manufacturing technology of energy-saving power devices, with a focus on the wide band-gap semiconductor material 4H-SiC.

Power Device Materials

Table 1 shows materials that may be used for power devices (excluding oxide materials) along with their typical physical constants.[1] In the table, BFM (Baliga's Figure of Merit for power-switching) and BHFM (Baliga's Figure of Merit for high-frequency power-switching) are performance indices related to on-resistance and high-speed switching. Of all the power device materials used, diamond rises above the others in terms of its physical properties. Research into epitaxial film formation has been carried out on diamond substrates at temperatures up to 1000 ℃, and has been carried out using microwave plasma CVD with CH_4 and H_2. Other research topics have also been pursued, such as adding boron and phosphorous for p-n control. Although there are issues with diamond, such as obtaining substrates and establishing the technologies for device manufacturing, it is a promising material for the power devices of the future.

Although silicon does not compare favorably to diamond in physical aspects, it is easy to obtain silicon substrates with an intrinsic carrier concentration, and there are mature device manufacturing technologies available such as p-n control, epitaxial growth and thermal oxidation.

To produce a power device with something other than silicon, a material with a performance at least as good as that of silicon will naturally be needed. With current trends toward energy conservation, there is a need for devices with low energy-loss (high efficiency) and a compact system profile, and the materials with the greatest potential are 4H-SiC and gallium nitride (GaN). These materials must meet the standards for use in power device requirements, providing high voltage resistance, low current leakage, a normally off feature, unipolarity, a low on-resistance (high channel mobility) and current collapse control. Circuit technology for power conversion is also important. Device candidates include Schottky barrier diode (SBD), MOSFET, JFET and SIT.

4H-SiC Device Applications

Using 4H-SiC single crystal growth, both homoepitaxy and p/n layer formation are possible. Because this produces quality single crystals, 4H-SiC can be used for vertical device applications. At SAMCO, we are directing our attention to trench MOSFETs, using chlorine reaction gas and fluorine reaction gas for reactive-ion etching (RIE) of 4H-SiC. When creating a trench MOSFET, the most important elements are applying the RIE process to create a smooth trench sidewall, for forming the gate and to create a rounded (notch-free) trench bottom. Figure 1 shows the results after using a fluorine gas in inductively coupled plasma RIE. The mask was formed with RIE after covering the entire surface with silicon dioxide in the photolithography process. Although notch-free RIE was achieved, the width after RIE was greater than that of the silicon dioxide mask and was bowed, so that the mask had to be modified to a vertical shape while maintaining the width. This can be improved easily by using ionic RIE. However, the silicon dioxide mask caused vertical lines to occur in the sidewall of the trench. Currently, ionic and radical RIE are being investigated from the perspectives of balance and sidewall protective films, and an ICP-RIE process suited to this goal is under development. Dr. Matsunami (Professor Emeritus) and Dr. Kimoto (Professor) of Kyoto University have provided us with advice on 4H-SiC devices through the Kyoto Nanotech Cluster Project. The problem in developing a practical silicon carbide MOSFET is a channel mobility of tens of cm²/V•sec because of the interface state due to Si_xC_yO formed in the SiO_2 (thermal oxidation)/SiC interface.

This phenomenon is thought to be caused by the on-resistance not falling. Dr. Tokumitsu, Assistant Professor at the Precision and Intelligence Laboratory at the Tokyo Institute of Technology, has produced interesting results by using an approach of low-temperature film formation to improve the channel mobility.[2] Low-temperature film formation is the direction we have taken in development at SAMCO. Our aim is to evaluate device properties by forming films with our PD-220LC plasma CVD device. Our target for channel mobility is at least 200 cm²/V•sec.

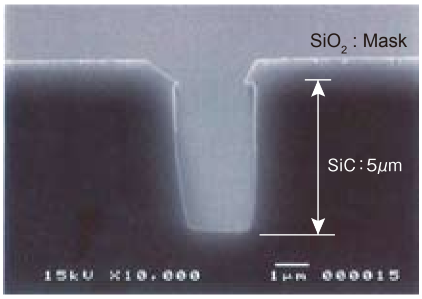

Fig. 1. Cross section of a silicon carbide trench

Conclusion

In this article, we have discussed the approaches we are taking at SAMCO to develop silicon carbide power devices, including the use of ICP-RIE devices, plasma CVD devices, power device materials processes, film formation processes and device development. A practical SBD has been developed recently, composed of 4H-SiC —a promising material for power devices. We expect to accelerate our development of practical applications. By further improving device performance, we are making a difference in the power device field.

References

*1 Takashi Shinohe: Silicon Carbide Power Devices, Toshiba Review, vol. 59, No. 2 (2004), authors: Dr. T. Paul Chow, et al.

*2 T.Hatayama, S.Hino, N.Miura, T.Oomori, E.Tokumitsu: Remarkable Increase in the Channel Mobility of SiC-MOS FETs by Controlling the Interfacial SiO_2 Layer Between Al_2O_3 and SiC,IEEE Transactions on Electron Devices.
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Table 1. Typical physical constants of wide band-gap semiconductor materials

Material	Diamond	GaN	4H-SiC	6H-SiC	3C-SiC	GaAs	Si
Band gap E_g (eV)	5.45	3.39	3.26	3	2.2	1.4	1.1
Electron mobility μ_e (cm²/V•s)	2,200	900	1,000/850	800/400	900	8,500	1,400
Hole mobility μ_h (cm²/V•s)	1,600	150	115	90	40	400	600
Insulation breakdown electric field strength E_c (MV/cm)	10	3.3	2.5	2.8	1.2	0.4	0.3
Saturation mobility V_{sat} (10^7cm/s)	2.7	2.7	2.2	1.9	2	2	1
Intrinsic carrier concentration n_i (cm^{-3})	1.6×10^{-27}	1.9×10^{-10}	8.2×10^{-9}	2.3×10^{-6}	6.9	1.8×10^{-6}	1.5×10^{10}
Heat conductivity λ (W/cm•K)	20	2	4.9	4.9	4.9	0.5	1.5
Dielectric constant ε_r	5.5	9	9.7	9.7	9.7	12.8	11.8
Bulk growth of substrate	In research stage	Difficult to obtain	Available	Available	Difficult to obtain	Easily obtainable	Easily obtainable
Direct/Indirect	I	D	I	I	I	D	I
BFM (for silicon) $\varepsilon_r\mu_e E_c^3$	27,128	653	340	191	30	16	1
BHFM (for silicon) $\mu_e E_c^2$	1,746	78	50	25	9	11	1