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Technology Trends of CZ-Silicon Substrates for Power Devices

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Introduction

As energy saving, a hybrid car, a solar cell, wind power, etc. are expanded rapidly. High performance is required of the power device as the control, and the demand is increasing rapidly. Although there is also a motion which adopts a wideband gap device as the power device, adoption of productivity and reliability to Si device is in use. Under such a situation, the development which replaces n type Si substrate for power devices with the large diameter of 200mmϕ from the small diameter of 150 or less mmϕ is hurried.

Si substrate is roughly divided into objects for high-voltage power devices, such as Pw-MOS and IGBT, and low-voltage power devices, such as MOS-FET.

Since the high-speed switching characteristic, the high breakdown voltage characteristic, and the low on-state voltage characteristic are required of a high-voltage power device, the substrate needs the silicon crystal which does not have a crystal defect in the whole at high resistivity. And with a large diameter wafer, the not an epitaxial wafer of a thick film but bulk (FZ/MCZ (Floating Zone growth / Magnetic Czochralski growth) substrate are chosen to the reduction in cost, and mass-production. The merit and subject at the time of choosing a NTD(Neutron Transmuted Doping)-MCZ board as a power device are reported.

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On the other hand, reduction of on-state resistance is required of Si substrate for low-voltage power devices for the reduction in power consumption. n type very low resistivity is required as substrate of this epitaxial wafer. The subject of this n type heavy doped substrate is also reported.

NTD-MCZ-Si wafer for high-voltage power device

FZ crystal of the large diameter of 200mmϕ is high cost. So, the very low oxygen MCZ crystal which large diameter technology has established is chosen [1]. The MCZ crystal of very low oxygen below 5E17atoms/cm^3 (ASTM F 123-79) can control generating of complex defects which degrade the device characteristic. As a Phos doping method of a MCZ crystal, there are the method of doping to the Si melt and the NTD method using a nuclear reactor.

The resistivity variation by the dopant striations in alignment with growth striations as the crystal doped to Si melt is large. The NTD method is irradiating a thermal neutron (<1eV) at ^{30}Si as isotope contained 3.09% in Si crystal, and carries out a conversion dope ^{31}P. Since the resistivity striations in alignment with growth striations do not exist, the advantage of a NTD crystal is that resistivity change is very small.

There is the following problem in NTD irradiation of Si crystal of large diameter; (1) There are few NTD nuclear reactors which can irradiate Si crystal of the large diameter of 200mmφ, (2) NTD irradiation may become uneven because of large diameter, (3) Since recovery-heat treatment is low temperature, the irradiation damage on a fast neutron (>1MeV) may be unable to be recovered. As the crystal of small diameter below 150mmϕ, there is a diffusion deposition process on long time at high temperature, and the irradiation damage was fully recovered. It is difficult to adopt the high temperature recovery process of diffusion deposition from the strength problem of 200mmϕ wafer.

We evaluated NTD irradiation using two heavy-water reactors and two light water reactors. The irradiation conditions of NTD are as follows; (1) Cd ratio ($n_{thermal}/n_{fast}$) of the nuclear reactors is from 5000 to 6, (2) The amount of fast neutron irradiation is to 1.9E14 to 8.5E16 n_{fast}/cm^2. (3) The target resistivity is to 13 to 60 Ωcm. After the NTD irradiation by these conditions, the thermal recovery of the irradiation defect by NTD was considered [2].

Although the defect by the γ ray produced in the conversion process by the thermal neutron of NTD is extinguished by annealing to 400 °C, complex defects, such as Di-vacancy (1.7μm), A-center (V-O_0, 831 cm^{-1}), (V-O-, 888 cm^{-1}), and C(III) (O-Ci, 862 cm^{-1}), occur by the accompanying fast neutron. These defects are recovered by 800 °C heat treatment, although it generates also with a heavy-water reactor as shown in Figure 1. The cluster damage exceeding 2nm is reported by 5E19 n_{fast}/cm^2 in the light water reactor. Although cluster damage was observed by 8.5E16 n_{fast}/cm^2 irradiation with the light water reactor this time, it is recoverable by heat treatment of 1000 °C or more. However, it may not recover depending on heat treatment.

NTD damage with a heavy-water reactor is recovered by low-temperature heat treatment of 1000°C or less. On the other hand, 1000°C or more need to be heat-treated for NTD damage recovery with a light water reactor.

NTD in 200mmϕ large substrate has the desirable heavy-water reactor recovered by low -temperature heat treatment.

n++ substrate of epitaxial wafer for low-voltage power device

Since it is a device demand to reduce on-site resistance as much as possible, the demand to dopant of a substrate is making it the highest possible concentration. However, although it is conflicting, the smaller one of the diffusion coefficient of dopant is desirable.

Here, comparison examination of which n type dopant should be chosen is carried out.

(1) In order to obtain high-concentration (or low resistivity) substrate, solid solubility limit is so desirable that it is large. Solid solubility limit of As is as the largest as 1.8E21 atoms/cm^3 (<0.1 mΩcm), and one of Phos continues. Solid solubility limit of Sb is as small as 7E19 atoms/cm^3 (1.1 mΩcm), and very low resistivity is not obtained in Sb doping.

(2) In order to prevent diffusion of dopant to a epitaxial layer, it is so good that a diffusion coefficient is small. Compared with the diffusion coefficient of Sb and As, the diffusion coefficient of Phos is large a single figure. Therefore, diffusion of Phos to an epitaxial layer may become a problem during device heat treatment. As a conclusion, when it thinks from the position of diffusion, as dopant of very low resistivity, As is desirable.

(3) If dopant becomes high concentration, a depression of freezing point will be caused, constitutional supercooling will occur, and a single crystal will not be obtained. It is easy to generate constitutional supercooling with As doping of 2 or less mΩcm, and with Phos doping of 1 or less mΩcm.

(4) Since Sb, As, and Phos as dopant tend to evaporate from Si melt in high concentration, it is hard to grow Si single crystal. Since Phos of an evaporation rate is small a single figure compared with As, growing of a Phos-doped Si crystal is easier than As-doped Si crystal growing.

Now, commercially, it is supplied as a heavy-doped substrate, by 10 or more mΩcm by Sb doped, in 10 to 2 mΩcm by As doped, and, in 2 to 1 mΩcm by Phos doped. In order to lower on-state resistance from now on, the n++ substrate of 1 or less mΩcm is required. As with a diffusion coefficient small a single figure compared with Phos and the largest solid solubility limit will be adopted as dopant.

On the laboratory level, in heavy As-doped Si crystal growing, generating of constitutional supercooling was able to be controlled and doping As concentration was able to be extended to 0.3 mΩcm as shown in Figure 2. Mass production of this heavy As-doped Si crystal is a future subject.

Summary

As a substrate of 200mmϕ large diameter for high-voltage power devices, the MCZ-Si crystal of the very low oxygen which NTD(ed) is chosen. It is reservation of a heavy-water reactor with little fast neutron damage which can perform NTD irradiation of 200mmϕ Si crystal.

In order to obtain substrate of epitaxial wafer for low-voltage power devices which reduced on-state resistance more, the crystal of 1 or less mΩcm needs to be developed. And development of As dope crystal with a small diffusion coefficient is desired from Phos. On the laboratory level, 0.3 mΩcm is attained as an As heavy-doped Si crystal.

References

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[2] K. Kashima et.al., 19th Annual IEEE Power Electronics Specialists Conference, p.1339(1988).

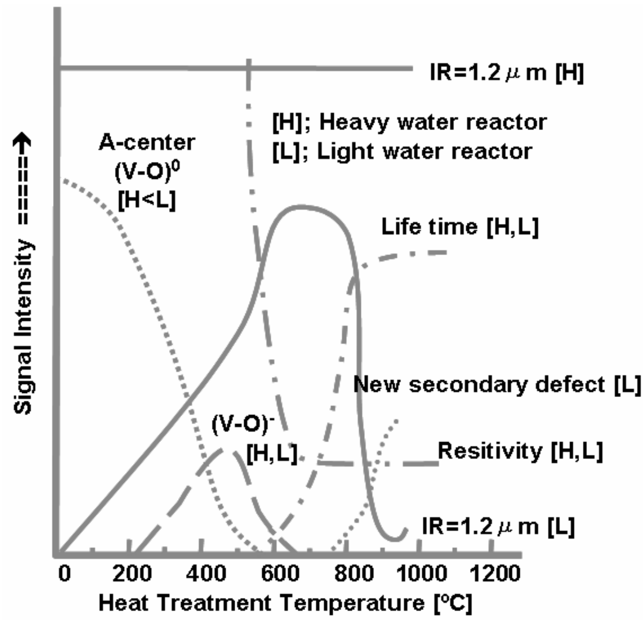

Fig. 1 Schematic diagram of recovery by heat treatment of neutron irradiation defects.

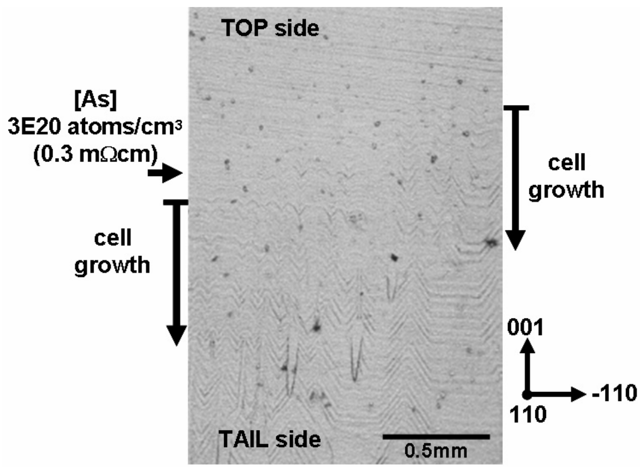

Fig. 2 In high concentration As doped CZ-Si crystal growth, cell growth generated by constitutional supercooling.