Estimation of Future Demand for Neutron-Transmutation-Doped Silicon Caused by Development of Hybrid Electric Vehicle

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1. Introduction

Neutron transmutation doping (NTD) is defined as a process of creating impurities in an intrinsic or extrinsic semiconductor by the neutron irradiation to increase their value for various uses [1,2]. NTD for the silicon semiconductor is based on the conversion of the ^{30}Si isotope into a phosphorus atom by the neutron absorption reaction as follows,

$$^{30}Si(n,\gamma)^{31}Si \rightarrow {}^{31}P + \beta^- \ (T_{1/2}=2.62h).$$

By using this doping method, silicon semiconductors with an extremely uniform dopant distribution can be produced. They are usually used for high power devices such as thyristor (SCR), IGBT, IGCT and GTO.

Now, the demand for high power semiconductor devices has increased rapidly due to the rapid increase of the green energy technologies. Among them, the productions of hybrid cars or fuel cell engines are excessively increased to reduce the amount of discharged air pollution substances, such as carbon dioxide which causes global warming.

It is known that the neutron-transmutation-doped floating-zone (FZ) silicon wafers are used in insulated-gate bipolar transistors (IGBTs) which control the speed of the electric traction motors equipped in hybrid or fuel cell vehicles. Therefore, inevitably, it can be supposed that the demand of the NTD silicon is considerably increased. However, it is considered likely that the irradiation capacity will not be large enough to meet the increasing demand. After all, the large irradiation capacity for NTD such as a reactor dedicated to the silicon irradiation will be constructed depending on the industrial demand for NTD silicon [3,4].

In this work, we investigated the relationship between the hybrid electric vehicle (HEV) industry and the NTD silicon production. Also, we surveyed the prospect for the production of the HEV. Then, we deduced the worldwide demand for the NTD silicon associated with the HEV production. This work can be utilized as the basic material for the construction of the new irradiation facility such as NTD-dedicated neutron source.

2. Methods

NTD method is applied for doping of the floating zone silicon crystal. The doped silicon is usually used for power devices because they necessarily require high breakdown voltage, low on-resistance and fast switching characteristics. Especially, the increase in blocking voltage of power devices can be achieved by application of the NTD silicon wafer [5]. One of the most important applications of power devices is the speed control of electric motors used in the industry and transportation.

A hybrid electric vehicle (HEV) is a hybrid vehicle which combines a conventional propulsion system with a rechargeable energy storage system like additional electric motors. HEVs became widely available to the public in the late 1990s with the introduction of the Honda Insight and Toyota Prius.

In the case that we estimate the future demand for the NTD silicon in the amount of 6 inch silicon ingots, the gross amount of NTD silicon needed for hybrid electric vehicle (HEV) per year can be described by

$$M = A \times t \times d \times \frac{N_M \times N_{IGBT}}{k} \times N_{HEV} \qquad (1)$$

where,
A: area of the 6 inch silicon wafer
t: thickness of the silicon material needed for a wafer
d: density of the silicon material
N_M: number of the IGBT module needed in a HEV
N_{IGBT}: number of the IGBT die needed in a module
k: number of the IGBT die obtained on a 6 inch wafer
N_{HEV}: number of the HEV produced in a year

At present the large crystals are cut using the multi-wire slicing technology with a small kerf loss of about 180 μm. The standard thickness of the commercially available 6 inch silicon wafer is 675 μm. With considering the kerf loss and polishing process, we assumed that the thickness of the silicon material needed for a wafer would be 1.2 mm.

The number of the IGBT module needed in a HEV was supposed to be 3 because the hard type HEV like Toyota Prius needs two inverters and a converter for a generator, for a motor and a booster for battery.

The number of the IGBT die needed in a module is dependent on the size of the IGBT die. It is known that 24 dies in 10×10 mm^2 size, 12 dies in 15×15 mm^2 size or 6 dies in 20×20 mm^2 size are needed in an IGBT module respectively.

The number of the IGBT die obtained on a 6 inch wafer can be deduced by

$$k = 3.14 \times D \times \left(\frac{D}{4A} - \frac{1}{\sqrt{2A}} \right) \quad (2)$$

where, D is the diameter (mm) of the wafer, and A is the area (mm^2) of the each IGBT die.

3. Results

From the above information, the amount of the NTD silicon needed for a HEV was obtained as follows;

50% of a 6 inch wafer for 10×10 mm^2 IGBT die;
64% of a 6 inch wafer for 15×15 mm^2 IGBT die;
67% of a 6 inch wafer for 20×20 mm^2 IGBT die.

There are many prospects for the future trend of the HEV market. Among them, several results are introduced in Table 1, and the new HEV production in each year is represented in the Table. We predicted the HEV production somewhat conservatively on the base of the other results. From the estimation, we could calculate the amount of NTD silicon needed in the future as in the table.

Table 1. Several prospects for the future production of the HEV and predicted need for the 6 inch NTD-Si ingot.

	2010	2012	2013	2015	2020	2030
Wards Auto	1					
J.D. Power			0.87			
EPA						50
CAR		1				
McKinsey					14	
Quality Metrics						55
IFX	2					
Hybridcars.com	1			2.2		
SUNCO				5.5		
HIEDGE	1.6	2.9	3.7	4.4		
Present expectation	1			3	10	50
						in million vehicles
Need for 6 inch NTD-Si ingot (tons)	25-33			75-99	250-330	1240-1640

From the Table, it can be seen that over 1200 tons of NTD silicon will be needed in 2030 by means of only a demand of the HEV market.

This estimation can be threatened by the following;

- The uncertainty of the electronic information on the estimation;
- The development of other technologies such as SiC and epitaxy;
- Environmental change in the development of the HEV.

Therefore, much more detailed analysis on above items is needed in the future.

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