NTD SILICON; PRODUCT CHARACTERISTICS, MAIN USES AND GROWTH POTENTIAL

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ABSTRACT

Topsil is a specialised manufacturer of ultrapure float zone silicon since 1959, headquartered in Denmark. Topsil co-pioneered the invention of Neutron Transmutation Doped (NTD) monocrystalline silicon with research institute Risoe in the 1970s and has since then been world leading manufacturer of NTD silicon for the power market. This presentation will focus on NTD silicon; its characteristics, invention and main uses. It will address the trends of the power market and market projections for NTD, and discuss the growth potential in the years ahead, including larger silicon wafers and management of the NTD supply chain.

1. Introduction

In 1951 Karl Lark-Horovitz was the first scientist to describe the possibility of using neutron transmutation for converting silicon atoms to phosphor atoms for the production of silicon semiconductors with a uniform distribution of the dopant [1], but it took more than two decades before neutron transmutation doping (NTD) of silicon found its way to a commercial breakthrough and an industrial production was initiated.
During the same time, Danish Master of Engineering Dr. Haldor Topsøe started to develop the silicon niche technology, float-zone, as a side-line to the production of his other business activities. In the late 1950s he built a new production plant in Northern Sealand, Denmark, and Topsil was founded. For the next two decades Topsil produced ultra-pure "hyper pure silicon" (HPS) refining the cleanliness of float-zone silicon. In 1974 Topsil became aware of a new method of doping silicon by the use of neutrons from reactors being developed in Germany [2]. In order to set up a test irradiation Topsil contacted the Isotope Laboratory at RISOE National Laboratory which operated the Danish reactor DR2 nearby Topsil. In the beginning RISOE scientists were sceptical of tests as previous experience had shown that silicon would be too radioactive for use after irradiation. Nevertheless a test irradiation was agreed which proved that the cleanliness of the silicon had reached a level where it could be returned to Topsil, just a few days after irradiation. Shortly after a pilot production for a German customer wanting to use the NTD silicon for thyristors in an American based power plant project was initiated. After customer tests of the pilot production Topsil obtained the order and by joining forces Topsil and RISOE National Laboratory co-pioneered the industrial production of NTD silicon [3].
NTD silicon is used when the semiconductor device requires high precision and uniformity of the phosphor dopant in the silicon lattice. Since the 1970s NTD silicon has established itself as the preferred material for power semiconductors which is the major market for silicon of this extremely clean and uniform quality.
In this paper, the characteristics of neutron transmutation doped (NTD) silicon will be described, its uses and applications, improvement opportunities, pointing to an overall market outlook.

2. Characteristics of NTD Silicon

Use of semiconductors for power electronics requires unique material characteristics because of the high power levels flowing in the devices. Non-perfect semiconductor crystals with non-uniform properties will render the power devices unstable with a potential dangerous impact on many everyday activities. Silicon is by far the most perfect semiconductor and therefore silicon is the preferred material for power semiconductor devices. Since the early 1970's the use of large monocrystalline silicon material has grown rapidly, and tremendous efforts have been made to develop techniques for growing perfect Si crystals with ever increasing dimensions. These crystals are the basic material for a wide range of electronic and optoelectronic devices.
For the power devices to work at designated power levels and voltage readings it is necessary to dope the silicon with impurities that enable current flow through the bulk of the silicon. Doping silicon crystals with phosphorus by neutron irradiation is the most superior technique in terms of doping control and it effectively removes non-uniformities in the high resistivity silicon crystal.

NTD products are characterised by their low resistivity variations within the individual wafers, from wafer to wafer in the same batch and from crystal to crystal. This requires accurate control of the irradiation dose and control of the undoped silicon growth process. An additional important control parameter is the minority carrier bulk lifetime which is measured after re-crystallisation to ensure that the state of the bulk is recovered and ensuring that the irradiation induced defects are annihilated.
The neutron irradiation damages the crystal lattice of silicon and these defects must be removed before use of the NTD silicon for device making. This is done by annealing the silicon at elevated temperatures in clean furnaces after irradiation [4]. The hardness (energy distribution) of the neutron spectrum in which the silicon is irradiated plays a crucial role for the defect generation and although most defects are annihilated by subsequent processing irreversible defects can occur. Irreversible defects are especially critical for products with low dopant density (high resistivity target) which therefore need to be irradiated in a well moderated/thermalised neutron spectrum.

The undoped silicon crystals are neutron irradiated in vertical or horisontal channels beside the reactor core. The crystals have diameters of up to 200 mm and typical lengths of up to 60 cm during irradiation. In case of an inhomogeneous neutron flux the resistivity profile of the doped silicon crystal will be influenced. With today's tight requirement of resistivity tolerance often down to ±5% it is therefore of great importance to control the flux profile during the irradiation. A solution to an inhomogeneous neutron flux is flattening of the flux at the expense of intensity [5].

NTD products are all about restricting the bulk resistivity variations beyond what is obtainable with any other means of producing n-type phosphor doped silicon. The radial resistivity variation (RRV), defined as

$$RRV = \frac{R_{Max} - R_{Min}}{R_{Min}} * 100\% \qquad (1)$$

where R_{Max} and R_{Min} are the maximum and minimum resistivity measured on individual wafers, is a crucial feature of each wafer cut from the NTD crystals. It is the most important factor to control in the silicon industry, because power semiconductor manufacturers cannot allow for high variations across the wafers cut from the crystals.
The bulk RRV of the starting undoped silicon material imposes some limitations to the minimum obtainable NTD bulk RRV, but if the average resistivity of the undoped silicon is sufficiently high, NTD RRV can be kept low [6]. An important contribution to keep the RRV low

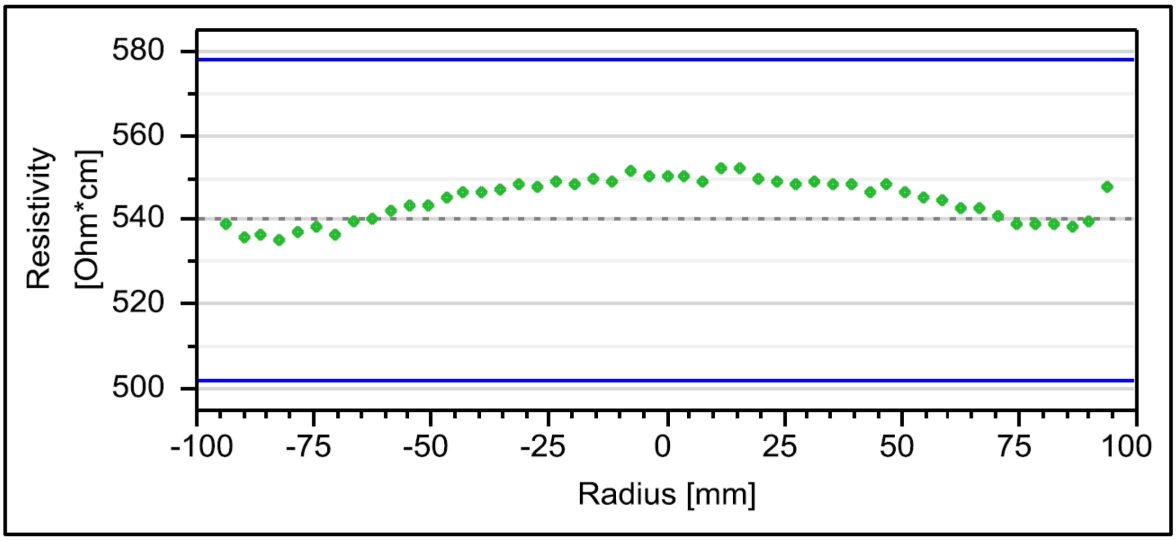


Figure 1: A typical 200 mm NTD wafer radial resistivity profile.

is radial rotation of the silicon during irradiation. Without radial rotation the silicon will be useless. A typical 200 mm wafer radial resistivity profile is seen in figure 1.

Beside the bulk RRV the local resistivity variation also known as resistivity striation is an important factor. The resistivity striation is one of the factors in which the nature of the NTD process has a large advantage compared to the gas phase doped silicon (PFZ) in which the doping takes place during crystal growth [7]. In gas phase doped silicon where dopants are introduced during growth of the crystal typical resistivity striation will be around ±15%. The case is the same for the undoped starting material for NTD but due to the nature of NTD, resistivity striation is not detectable after irradiation, see figure 2.

A comprehensive description of the NTD process is found in the IAEA publication regarding NTD silicon [8]. Typical requirements for NTD products are seen Table 1.

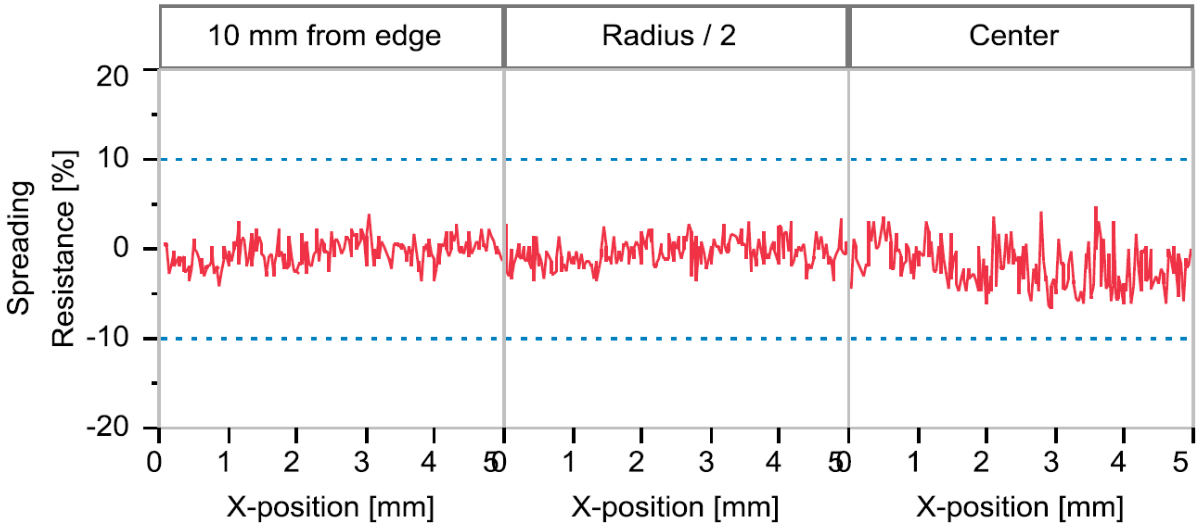


Figure 2: Typical striation of a NTD wafer. It is seen striation is not detectable, only noise is seen.

Resistivity Tolerance	±5 %
Radial Resistivity Variation	<6%
Resistivity Striations	Not detectable
Minority Carrier Lifetime	>500µs

Table 1: Typical requirements for NTD products.

Neutron transmutation doping of silicon is today done at research reactors worldwide. The main purpose of these reactors is as the name indicates research. For silicon manufactures the reproducibility is very critical especially due to the narrow tolerances needed for power components to work. Today manufactures of silicon for high power devices are expected to be certified according to the quality management system of ISO/TS 16949:2009, which focuses on continued improvements, prevention of defects, and minimising variation and waste throughout the supply chain. Neutron irradiation sites are expected to be certified according to ISO 9001:2008. Managing changes to or around the process is a very important field to address when dealing with NTD silicon. Very small changes can potentially completely alter the electrical properties of the silicon and hence the performance of electronic devices. Changes in the reactor (e.g. new equipment installations, experiments etc.) therefore also must be assessed in relation to possible influence of the quality of the NTD product.

3. Applications, Market Trends and Future Expectations

Due to its high resistivity and uniform resistivity distribution, NTD silicon is primarily used in advanced, high and very high power devices (above 1.2kV) on the power market. Typical examples of such devices are thyristors (fig 3), rectifiers, insulated-gate bipolar transistors (IGBTs) and power metal oxide semiconductor field-effect transistors (MOSFETs).

Applications

Figure 4 below showcases the final application of NTD silicon compared to other selected substrates on the power market. It is noted that NTD is applied in the most demanding end user applications, mainly in the transportation, energy infrastructure and industrial sectors.

Fig. 4: Select substrates on power market, Topsil

Fig. 3: Thyristor

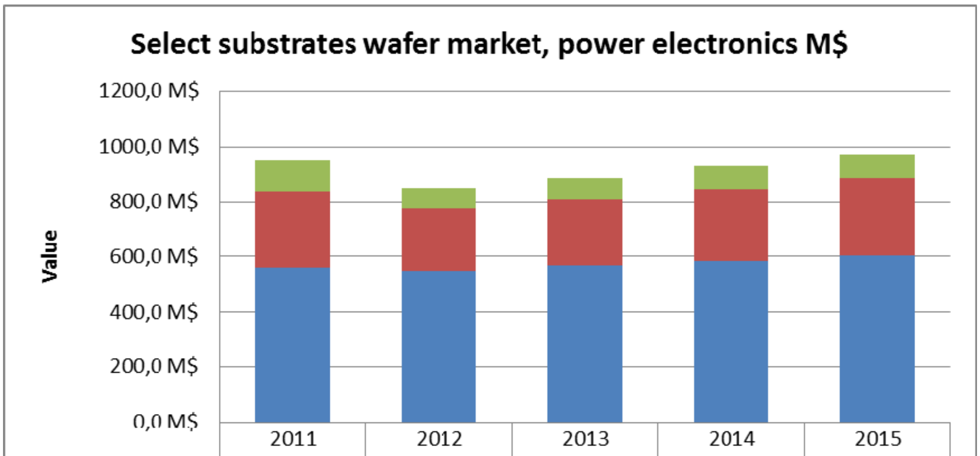
Fig 5: Example of high-voltage direct current (HVDC) system built from thyristors or hundreds of IGBTs

As further appears from figure 4, use of the various substrates applied in power devices overlaps. Over time silicon technologies mature and evolve. For instance, gas doped silicon (PFZ) nowadays finds its application in electrical components above 1.2kV, previously requiring NTD silicon, targeting the lower voltage levels. For some power device makers, PFZ seems to be the preferred choice over such NTD, due to the fact that although PFZ

substrate performance is well below the tight tolerances of NTD silicon, it does not involve the externally conducted neutron irradiation.
Despite ongoing technology development and the fact that the semiconductor industry and its suppliers continue to push the limits of other silicon substrates available to the market, to this day, however, no other substrate has attained the resistivity and resistivity distribution to replace NTD silicon in high power semiconductor devices. Furthermore by developing and maintaining a reliable NTD supply chain, it is possible to gain the benefits of this superior substrate while eliminating any concerns related to a safe supply.

Market Trends and Future Expectations
The demand for NTD silicon is in essence driven by three main factors: One being enhanced performance of other substrates (substitution) mentioned above, the second is global macro trends, answered by markets and government policy action, and finally the development and market introduction of new, advanced energy technologies.
In any economy, demand for energy is strongly correlated to economic activity. Furthermore, energy prices and possible subsidies play a key role in determining energy trends. For instance, population and prosperity growth in the BRIC countries (Brazil, Russia, India, and China) have amongst others resulted in higher demand for electricity, energy efficient solutions in energy infrastructure and industry, and more climate friendly transport of people and goods. This has a direct effect on the development of the transportation, energy infrastructure and industrial sectors.
On the other hand, when demand is up, the efficiency of current technologies becomes a key focus. Add to this environmental consideration, backed by targets for CO2 emissions. This altogether calls for the emergence of new and more efficient technologies, for conventional and renewable sources alike [9].

Figure 6 showcases the value of select substrates on the power market 2011-2015, actual and forecast, based on industry insights from Yole Developpement, independent analyst on the power market. Although expectations are positive, year on year, a severe unexpected drop by 36% of NTD silicon market value took place 2012 compared to 2011. Hence, in 2012 the aggregated NTD market targeting high voltage and very high voltage power components accounted for a value of around 73 M$ compared to 113M$ only a year before.



	2011	2012	2013	2014	2015
Si FZ NTD	113,2 M$	73,0 M$	77,2 M$	81,8 M$	87,0 M$
Si FZ PFZ	277,5 M$	228,0 M$	240,8 M$	260,1 M$	282,3 M$
Si CZ & CZ + Epi	558,0 M$	546,6 M$	568,5 M$	585,2 M$	602,3 M$

Figure 6: Wafer market development, power electronics, actual and forecast
(Yole Developpement, Feb. 2013)

The sudden market drop was caused by more factors. Most notably were the effects of the global economic downturn affecting the number of large scale politically driven projects being initiated worldwide, and furthermore, for various reasons large markets such as China stopped ongoing energy and transport projects short term. On the supply side, inventories were booming due to the fact that manufacturers had anticipated a demand which did not materialise (Yole Developpement, based on industry insights).

Well into 2013, the market for NTD silicon continues to be affected by inventory adjustments. The underlying macroeconomic trends have not changed however. What could drive demand forward short term are new large scale transport and energy infrastructure projects in the pipeline. For instance, China is pushing for approval of a massive upgrade of its state grid, involving a high-voltage direct current (HVDC) (figure 5) power corridor connecting distant supply and demand centres across its provinces and regions. The need for capacity is expected to grow from 1060 GW in 2012 to 1500 GW by 2020 [10]. Germany is considering a similar HVDC upgrade which is key to meeting its targets on reduced dependency on nuclear and fossil fuels. By setting up smart power systems based on HVDC, Germany will be able to better utilise its energy sources. For instance, energy generated by renewable sources of the North will be deployable in the more industrialised Southern part of the country [11].

The industry at large has set its expectations of growth of market size 2013-2015 in the range of 5-6% year on year (Yole Developpement, based on industry insights). As the recent past shows us, however, large scale politically driven projects being initiated or stopped in any major economy may have a substantial impact on this picture which we are not yet able to foresee.
Whether the market will grow short term or not, NTD technology, as well as other power silicon technologies, will continue to evolve. As with any other technology there will, on the one hand, be a pressure for increasing performance while, at the other, reducing lead times and price.
To sustain and increase the NTD market size, NTD silicon manufacturers must therefore continue to stay focused on delivering premium quality NTD, safely, in time, and at competitive prices. Larger size silicon wafers have been an outspoken request from the industry for some time now, as larger size wafers will aid drive manufacturing costs down. We will therefore see NTD silicon with a diameter of 200 mm for high power devices gradually gain a foothold in the assembly lines of the power semiconductor industry in the coming years combined with a continued push for substitute substrates long term. The main challenge, hence, remains to make sure that NTD silicon remains superior in technical performance and to continue to drive efficiency means forward at all levels of the NTD supply chain.

5. Summary

In summary, NTD is the preferred substrate targeting electrical high and very high power components. The long term trends for NTD silicon are favourable, and larger size wafers (200 mm) for high power are currently entering the supply chain. Possible substitute substrates long term, however, might pose a challenge to the otherwise favourable outlook. The main challenge for the NTD silicon supply chain therefore remains to stay ahead of competition by continually enhancing performance, reducing lead times, and by driving efficiency forward.

6. References

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