



APPLICATION NOTE

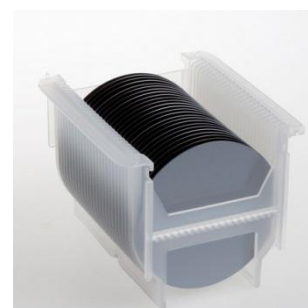
HiRes™
HIGH RESISTIVITY
SILICON FOR GHz &
THz APPLICATIONS

This note presents a silicon substrate that is well suited for microwave and millimeter wave circuits and devices. The silicon substrate is manufactured from High Resistivity HiRes™ Float Zone silicon to adapt to RF-IC and MEMS requirements for a low-loss GHz & THz carrier substrate.

Radio Frequency (RF) capable semiconductor processes face hard design conditions for wireless systems operating at GHz and THz frequencies. This is true not only for active devices where the design node is presently 90 nm on Czochralski silicon, but also for integrated passive devices. Preferably, the substrate for active and passive device integration should be electrically insulating to reduce parasitics and cross-talk. Substrate parasitics constitute one of the main bottlenecks for the integration of passive RF devices in integrated circuits (ICs). Also, the effective dielectric constant of the substrate should be high to enable a higher degree of integration. Czochralski silicon having bulk resistivities below 100 Ωcm is not electrically insulating and is thus not a suitable GHz and THz substrate.

High resistivity Float Zone silicon is a good candidate for a GHz IC substrate; that is a substrate for monolithic integration of digital, analog and interface functions on a single chip. At GHz frequencies high resistivity silicon can be considered an electrically insulating substrate with a high effective dielectric constant (Table I). With the advent of high mobility Si/SiGe epitaxial technology in the mainstream technology portfolio the Si based IC switching frequencies have been driven up in the very high GHz region (THz) enabling advanced wireless communication systems to be built on Si.

High resistivity Float Zone silicon as a basis for GHz active and passive devices has been extensively investigated in R&D environments and, recently, some of the devices have matured into products. In favour of using silicon is the mature technology platform, the substrate pricing and the availability.



Galliumarsenide (GaAs), which is presently the preferred choice for a microwave substrate does not have these features. Also, thermal conductivity of Si is much larger than that of GaAs. This is important when designing high power devices. Table I showcases the properties of high resistivity silicon and semiinsulating GaAs:

Semiconductor property (300K)	Semiinsulating GaAs	HiRes™ silicon
Bulk resistivity	$<10^8 \Omega\text{cm}$	$<10^5 \Omega\text{cm}$
Intrinsic carrier concentration	$1.79 \times 10^6 \text{ cm}^{-3}$	$1.45 \times 10^{10} \text{ cm}^{-3}$
Thermal conductivity	0.37 W/cm-K	1.5 W/cm-K
Dielectric constant	12.93	11.7
EPD	$<5,000 \text{ cm}^{-3}$	$<100 \text{ cm}^{-3}$
Electron Drift Mobility	$7,000 \text{ cm}^2/\text{V-s}$	$1,500 \text{ cm}^2/\text{V-s}$
Hole Drift Mobility	$400 \text{ cm}^2/\text{V-s}$	$500 \text{ cm}^2/\text{V-s}$
High Field Drift Velocity	$6 \times 10^6 \text{ cm/s}$	10^7 cm/s
Carbon content	$>5 \times 10^{14} \text{ cm}^{-3}$	$< 10^{16} \text{ cm}^{-3}$
EL2 concentration	$1.5 \times 10^{16} \text{ cm}^{-3}$	0
Light point defects $>0.3 \mu\text{m}$	<100	<10
Bandgap (300K)	Direct 1.42 eV	Indirect 1.14 eV
Epitaxial system	GaAs-AlGaAs	SiGe-Si, GaP-GaN
Lattice constant	5.658 Å	5.435 Å
Schottky barrier height (Typ.)	0.8 eV (n-type)	0.65 eV (n-type)
Oxide interface traps	$<10^{12} \text{ cm}^{-2}$ (PECVD oxide)	$<10^{10} \text{ cm}^{-2}$ (thermal oxide)

Table I Comparison of 300K properties between semiinsulating GaAs and HiRes™ silicon

High resistivity silicon is defined as monocrystalline silicon having a bulk resistivity larger than 1 kΩcm. Although Czochralski grown monocrystalline silicon is often specified up to 1.5 kΩcm, Float Zone grown monocrystalline silicon is the only growth technology that is able to have bulk resistivities above 1 kΩcm with good tolerance control of the resistivity along the ingot from where the silicon wafers is sliced. Topsil manufactures and sells Float Zone grown high resistivity silicon (HiRes™) with bulk resistivities approaching 70 kΩcm. Furthermore, the company's proprietary knowledge of keeping the radial resistivity variation low makes Topsil high resistivity ingots and wafers excellent candidates for future GHz & THz technologies based on silicon.

In the following sections an overview of the use of Float Zone silicon in processing microwave devices is given and some of the differences between Czochralski grown silicon and Float Zone grown silicon are addressed.

Float Zone silicon is by nature more pure than is Czochralski grown silicon. For this reason oxygen levels and other contaminant levels are intrinsically very low in Float Zone grown silicon. Bulk microdefects (BMDs) such as voids and

interstitial-type defects are absent in Float Zone grown silicon. The reduced oxygen level and the absence of BMDs have two important implications on device processing. The first is a much better control of the bulk electrical properties during processing and the second is the absence of internal gettering in Float Zone material.

Table II shows the specification for HiRes™ Float Zone silicon. Note that both p- and n-type silicon can be made with narrow resistivity axial and radial tolerances (Fig. 1 and Fig. 2) and a high degree of crystalline perfection. These material specifications are a result of a continuous R&D effort on the purification of silicon performed individually by Topsil or by Topsil in close cooperation with external R&D institutions.

Table III shows specifications for polished electronic grade and MEMS grade HiRes™ wafers. State-of-art wafering equipment is used to meet the tight mechanical specifications on HiRes™ wafers to ensure that the surface properties and the near-surface properties comply with the requirements for IC and MEMS processing.

Crystak/Bulk	Units	Physical properties
Orientation		<100>
Orientation tolerance	Degree	±1.0
Type		n/p
Resistivity range	Ωcm	1,000-50,000
Resistivity tolerance	%	±30 - ±50
Radial resistivity variation	%	<50 - <60
Striations	%	Not detect
Minority carrier lifetime	μs	>1,000 n-type, >500 p-type
Oxygen (new ASTM)	at cm ³	<2.0 x 10 ¹⁶
Carbon	at cm ³	<1.5 x 10 ¹⁶

Table II HiRes™ bulk ingot properties

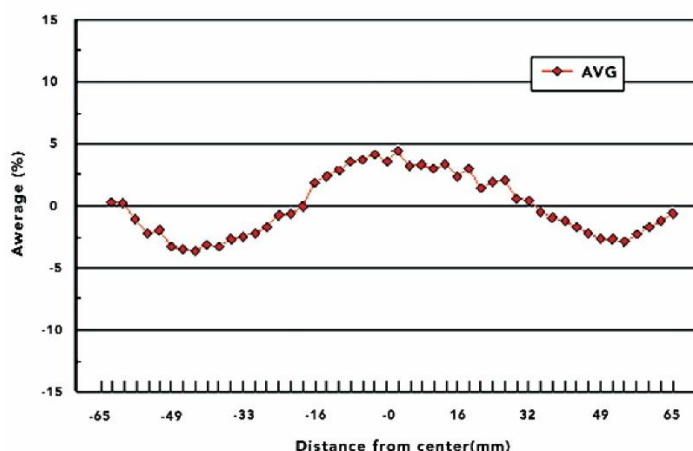
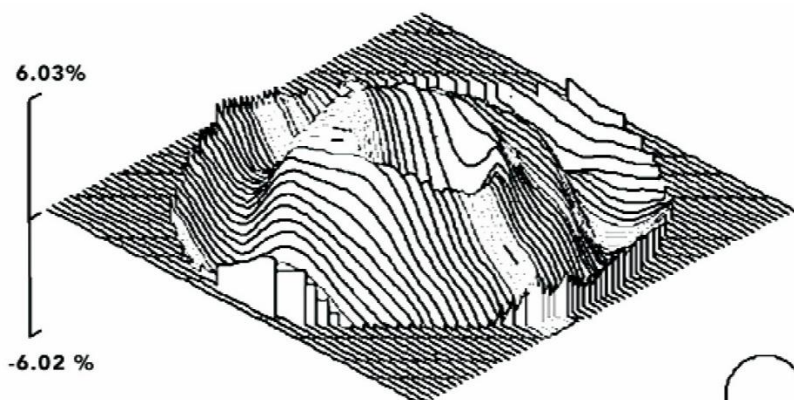


Fig. 1. Radial resistivity variation (RRV) for Topsil HiRes™ ingot.



HiRes™ wafer.



Fig. 2. Typical resistivity plot of Topsil

Single side and double side polished wafers	Units	150mm	200mm
Thickness	μm	>350	Min. 300 max 1300
Thickness tolerance	μm	±10	±5
Bow	μm	<30	-
Warp	μm	<30	-
TTV	μm	<2.5	<4
TIR (FPD)	μm	<1	<2
Particles	μm	<10@0.2	<10@0.3

Table III HiRes™ wafer specifications

The most basic structure in terms of a microwave device is a broadband Waveguide transmission line. Transmission lines are essential interfacing components in modern wireless systems, serving mainly as interconnects and impedance adjustments between different circuit building blocks. They connect antennas to transmitters and receivers and they are widely used as impedance matching for instance in RF mixers and amplifiers.

High resistivity silicon is an ideal candidate for a substrate for a GHz & THz transmission line because of the low loss tangent and, thus, the high effective dielectric constant. Several papers have demonstrated the usefulness of high resistivity silicon as a substrate for low loss waveguide transmission line devices. At 35 GHz the loss tangent is ~0.004 for a Si wafer having a bulk resistivity of 1 kΩcm. The loss tangent is even lower for a higher resistivity Si wafer.

Also, the use of high dielectric constant high resistivity silicon reduces radiation losses because most of the electromagnetic field is concentrated in the dielectric, but the major benefit in having a high dielectric constant substrate is in the subsequent packaging of the device, where package sizes can be decreased with approximately the square root of the dielectric constant. This is important in the ever ongoing miniaturisation of electronic systems. The dominant loss in high dielectric constant high resistivity silicon is conductor losses from the metallic strip conductor. Conductor losses originate from several factors related to the metallisation; that is the metal conductivity, skin effects and surface roughness of the substrate, the metal layer and the conductor side walls. With the advent of copper metallisations in the IC industry very low loss interconnects and transmission lines are expected when metallisation patterning issues have been fully resolved.

Transistors for use in RF power amplifiers are in high demand for wireless GHz applications. Galliumnitride-on-silicon (GaN) high-electron mobility transistors (HEMT) and silicon-germanium (SiGe) heterojunction bipolar transistors (HBT) challenges traditional RF lateral diffused MOSFETs (RFLDMOS) and gallium arsenide (GaAs) HBTs. As the operating frequency is driven even higher, high resistivity silicon comes into play for minimising parasitics, and is thus becoming an attractive substrate for SiGe HBTs, RF LDMOSFETs and for GaN HEMTs. High power added efficiencies (60-70%) at high frequencies (2-5 GHz) and good breakdown behaviour with low associated leakage current levels have proven that the combination of low loss, high resistivity silicon with IC manufacturing technologies create a viable path for future wireless systems operating at high frequencies.

Passive components, apart from transmission lines and interconnects, constitutes the biggest bottleneck in RF IC devices. Whereas CMOS based ICs can be managed without any passives, a circuit operating at GHz frequencies requires impedance matching between circuit building blocks. Thus, passive devices new to mainstream IC silicon technology are needed. The devices, like inductors, transformers and varactors, need to be fabricated with the highest possible quality factor (Q) so as to maximise power efficiency through the whole system. This can be done through a reduction of resistive losses and capacitive or inductive parasitics. RF MEMS components are emerging devices to solve many of these problems and they will make a major impact on wireless systems mainly because of their low insertion loss, good isolation properties, linear characteristics and low power consumption. Ultimately, low cost can be obtained when RF MEMS components can be integrated on an RF IC chip or can be put on the RF IC chip in a low cost post-processing step.

Capacitive switches, frequency selection band pass filters, inductors and tunable capacitors all rely on low dielectric losses for maximum Q values. High resistivity silicon again will be the preferred substrate, because dielectric losses will be minimised and because MEMS technology is a mature technology on silicon.

In summary, HiRes™ silicon is an excellent choice for a microwave substrate. The RF device properties obtained on high resistivity silicon are comparable to those obtained on GaAs, which is presently the most popular choice for a microwave substrate.

In terms of mixed-signal devices, silicon is superior to all other known electronic substrates, and with the extra benefits of using a high resistivity silicon substrate for mixed-signal devices operating at GHz frequencies, HiRes™ silicon is positioned well in the ongoing battle between price, performance and size of wireless electronic systems.

CONTACT

For more information please contact:

Field Application
Engineering
FAE@gw-
topsil.com

Topsil GlobalWafers A/S

Topsil is a world leading supplier of ultrapure silicon for the global semiconductor industry. Engaging in long term relations with customers, Topsil focuses on premium quality, an efficient production process and a safe delivery of products.

Float-Zone FZ silicon is the high-purity alternative to crystals grown by the Czochralski CZ method. Based on extensive knowledge, expertise and significant investments in new technology, facilities and equipment, Topsil FZ silicon products are ideal for the most demanding purposes in conversion and control of electrical power.

Topsil was founded in 1959. Situated near Copenhagen, Denmark, Topsil is part of the GlobalWafers Group with manufacturing presence in Europe, Asia and the US.

Topsil GlobalWafers A/S

Siliciumvej 1
DK-3600 Frederikssund
Denmark
Tel.: +45 47 36 56 00
E-mail: topsil@topsil.com

Internet: www.topsil.com
CVR no.: 37 84 22 22