Wurtzitic Boron Nitride on Diamond: The Ultimate Epitaxial Wafer for "Semiconductor on Insulator"

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ABSTRACT

In last four decades, the number of transistors of integrated circuits (IC) has been following Moore's Law to double in about every 18 months. This relentless densification of circuitry would require technological breakthroughs of many fronts such as nanom chemical mechanical planarization (CMP) for achieving a super smooth surface on an ultra flat wafer, and UV photolithography for imprinting nanom copper wires on it. However, with the circuitry going beyond ultra large-scale integration (ULSI), the noise level in the chip will increase that may challenge the material limits of semiconductor designs. The Second Law of Thermodynamics requires entropy to increase dramatically in a chip of super ULSI. Entropy may manifest as waste heat or scattered phonons, i.e., random vibration of atoms; and chaotic charges or intrinsic carriers, i.e. quantum fluctuation of defects. Both of them will increase the background noise that may overshadow the electrical signals that are processed in the future chip.

The ULSI chips for computer CPU have been using copper heat spreader to avoid overheating. However, copper with its thermal conductivity of 400 W/mK is proven incapable to chill the next generation Pentium IV with a speed of 4 GHz and a power of 120 W. Hence, Intel has decided in 2004, for the first time since Moore's Law took effect forty years ago, to use dual chips of slower speed and lower power for the next generation CPU.

In addition to be plagued by heat, the semiconductors are also haunted by the surge of intrinsic charge carriers that tend to concentrate with temperature. As a result, the current Pentium IV CPU is leaking 1/4 of its electricity into the background noise. The very material that constitutes the semiconductor is too conductive for packing transistors required by post ULSI chips.

Both problems of phonon scattering and charge fluctuations can be reduced by using more stable crystal lattice with strong atomic bonds. Diamond has the most stable lattice with the strongest atomic bonds. Hence, diamond is not only super hard, but also super resistant in electron movements. Moreover, diamond is super fast in transmitting sound and in ridding heats. In addition, diamond crystal lattice remains intact at temperatures that will burn out all other semiconductors. All these extreme attributes will make diamond the best friend of semiconductors. In fact, diamond itself is the ultimate semiconductor with its future performance that will make current semiconductors primitive like stone-age tools.

The highest thermal conductivity makes diamond the ideal heat spreader. The lowest charge fluctuation makes diamond the dream barrier substrate. Hence, semiconductor on diamond (SOD) can be the best semiconductor on insulator (SOI) that is envisaged for making future ULSI, laser diodes, LED, microwave (MW) generators, and other signal processing or optic-electronic devices.

Recently breakthroughs of CVD diamond film deposition and polishing technologies have made diamond substrates engineering possibility rather than research curiosity. For example, Kinik Company is now offering cost effective diamond wafers up to four inches that can substitute current substrate materials (e.g. sapphire, silicon carbide). Moreover, the super smooth (e.g. Ra about 2 nm) polycrystalline diamond film can be coated with wurtzitic boron nitride wBN) to become preferably oriented with hexagonal planes. The isostructural hexagonal AlN can be further over coated on wBN to make the surface fully compatible with nitride semiconductors that are used for fabricating high power semiconductors. The gradation from wBN to AlN with random to preferred crystal orientation is ideal for epitaxial deposition of Si, SiC, GaN, InN, GaAs or other semiconductors. Consequently, Kinik' DiAlN® wafers are suitable to make next generation devices of ULSI, LD, LED, MW that are

capable to operate at high frequency and large power. For example, DiAlN® wafers may be used to fabricate UV or even X-ray LED by widening the band gap of nitride semiconductors such as by doping GaN with smaller Al or B atoms.

The DiAlN wafer is also the dream substrate for making surface acoustic wave (SAW) filters with ultra high frequencies (e.g. 20 GHz) and larger power (e.g. for satellite communications). wBN is the strongest piezoelectric material; and, AlN, the second strongest. They can convert electromagnetic signals into sound waves, and vice versa. Current ceramic SAW filters (e.g. $LiTiO_3$, $LiNbO_3$) are thermal insulators that tend to heat up during the operation. They are also ionic conductors that will leak out electricity. In contrast, DiAlN is the most efficient thermal conductor and electrical resistor so it can be the dream SAW filters for future telecommunications.

Keywords: diamond film, wurtzite BN, AlN, ULSI, LED, SAW filter

1 THE SUPER SMOOTH CVD DIAMOND FILM

Diamond is the best insulator of all materials so it can be the ideal substrate for SOI. Diamond has a thermal conductivity that may approach 2000 W/mK (e.g. for perfect diamond) that is at least 10 times higher than common oxides. Consequently, SOD cannot only be operated with higher speed, but also with lower temperature.

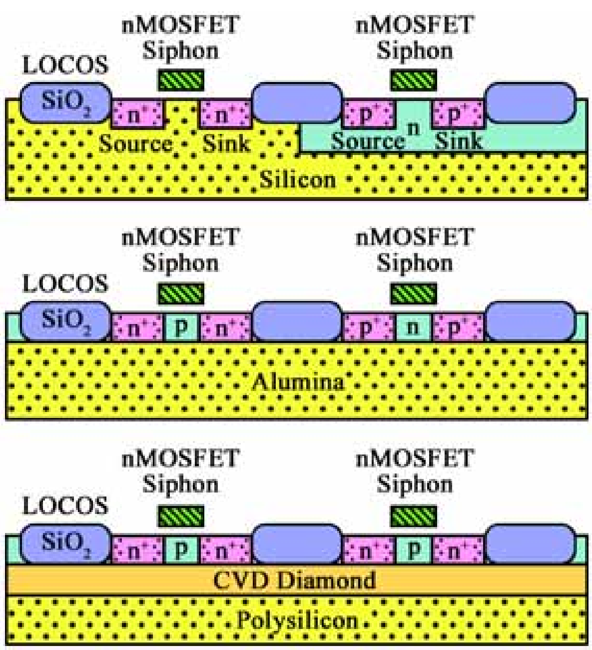

Figure 1: The isolation of transistors by insulating with oxide (top diagram) and the use of oxide substrate for further insulation (middle diagram). Semiconductor on diamond(SOD) is the most effective silicon on insulator (SOI). It also improves the heat dissipation.

Diamond film for SOD can be deposited on a suitable substrate (e.g. silicon wafer) by chemical vapor deposition (CVD). The CVD diamond film is then polished to achieve a mirror finish (e.g. Ra < 5 nm). Subsequently, semiconductor (e.g. silicon) can be deposited onto the smooth diamond surface.

2 EPITOMICAL WAFERS FOR LED

Current LED (or LD) wafers use sapphire or silicon carbide (SiC). AlN/wBN coated SOD are much superior than these commercial substrates. SOD is more insulating and it can dissipate heat fast, hence LED with SOD can operate at a much higher power. In addition, because the lattice mismatch is better, LED with SOD is much more energy saving and it can last much longer time. Furthermore, with the thin layers of AlN/wBN/diamond film used, the cost of SOD is competitive to thick single crystals of either sapphire or SiC.

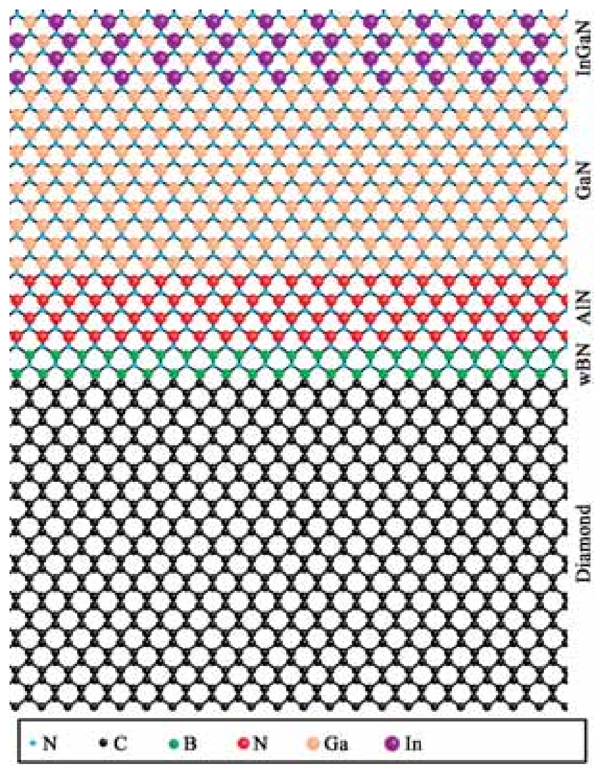

Figure 2: This atomic super lattice illustrates the gradation of the buffer layer to convert diamond lattice to wBN and then to AlN. Subsequently, GaN and InGaN may be deposited as LED or LD. The

relative atomic size is also shown as legends. The gradation of atomic size (as shown by colored circle) will minimize the boundary stress as well as the dislocation density. The lower the dislocation density, the more reliable is the device.

Based on the above epitaxial gradation, one example of making laser diode with SOD is illustrated below. Current LED are monochromatic so the white light must be produced by mixing colors (e.g. Red, Green, Blue). It is possible to dope nitride semiconductors (e.g. GaN) with smaller Al or even B atoms. The result is to bring atoms closer with the consequence of increasing the band gap. Hence, the wavelength of the light produced can be effectively shortened. With the doping of Al atoms, a UV LED can be fabricated. The UV LED can be used to excite phosphor with white fluorescence light. This LED fluorescence light is not only brighter than conventional fluorescent lights, but also it avoids the use poisonous mercury as the source of UV. Moreover, if B doping is also added, an LED may also become a convenient X-ray source without involving cumbersome vacuum chamber. The X-ray LED can be used in X-ray lithography for fabricating true nanom structures of MEMs, and the ultimate semiconductor chips that contain single electron transistors.

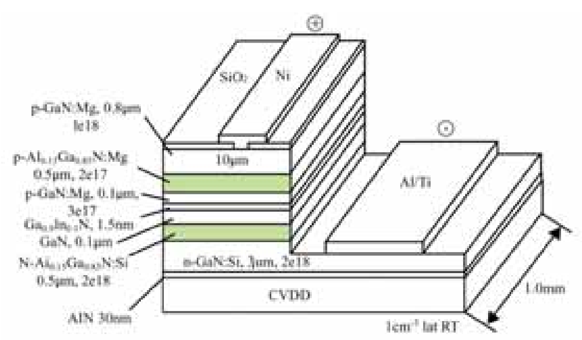

Figure 3: One example of making laser diode with SOD.

Although SOD is intended to be an insulator, for certain applications, the substrate may require electrical conduction as well (e.g. as an electrode). In this case, a metal conductor (e.g. copper) can be inserted in the diamond film to allow the passage of electrical current. The conductor can be isolated by insulating diamond or they can form alternative partitions. One example to fabricate such a conducting SOD is illustrated below.

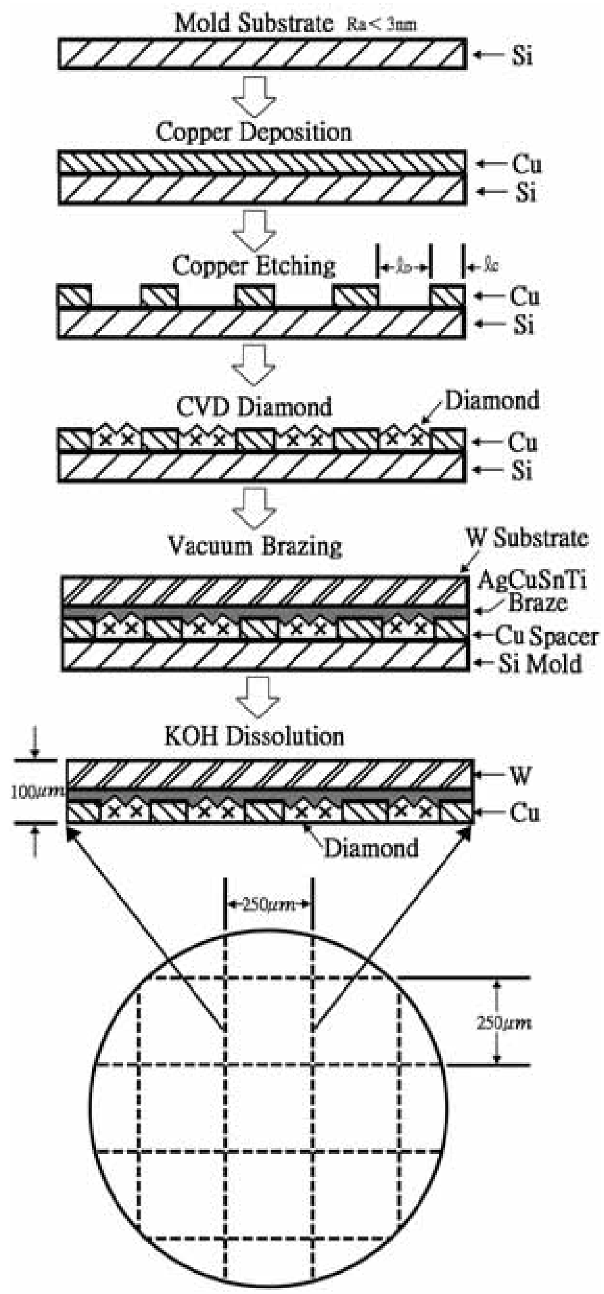

Figure 4: One example of fabricating SOD with an electrode for each square of diamond. Electrically conducting SOD is a useful design for LED or LD.

3 EPITOMICAL WAFERS OF SOD

The SOD with or without AlN/wBN coating can be used for a variety of applications. These applications can be much more powerful and reliable than current materials. For example, Intel's failure to make 4 GHz CPU in 2004 as described above can be corrected by making the 90 nm ULSI on SOD. Some examples of epitaxial wafer applications are illustrated as follows.

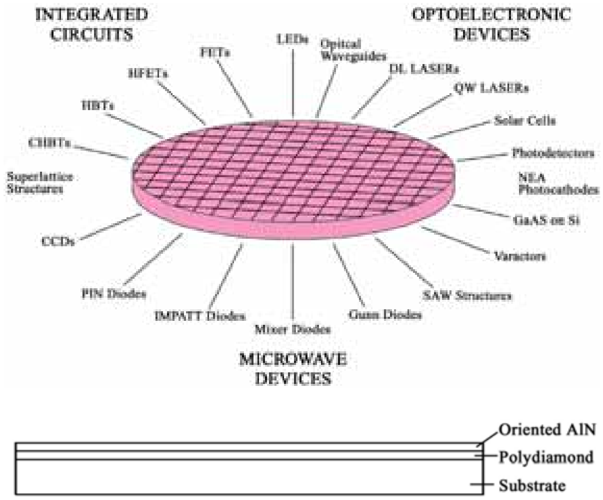

Figure 5: The examples of using SOD for making future semiconductor devices for ULSI, LED, MW, and much more.

Diamond epitaxial wafers up to six inches in size have been manufactured by Kinik Company with superb surface finish (e.g. Ra = 3 nm). They are ideal substrates of various applications.

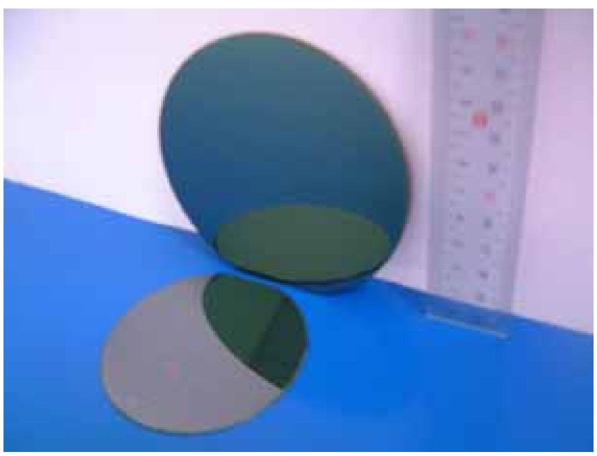

Figure 6: Diamond epitaxial wafers manufactured by Kinik Company in Taiwan.