SAW Filter with AlN on Diamond

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Abstract

Diamond surface acoustic wave (SAW) has been used to boost the frequency of thin film filters made of piezoelectric materials [1-3,13,14]. Many designs have been tested and with significant results, in particular, AlN on diamond (AlNoD) as the interface for transmitting Rayleigh wave was studied extensively [4-12,16-21]. However, in all cases, nano crystalline or microcrystalline AlN coatings were deposited, typically by sputtering or CVD, on polycrystalline diamond film. The diamond film itself may contain nano of micro grains that are deposited by CVD [4,5,7]. The presence of extensive grain boundaries in AlN can attenuate rapidly the propagation of Rayleigh wave. Moreover, the bonding between loose atomic packing of AlN and tight lattice of diamond is weak so much of the mechanical energy is dissipated as heat. In fact, the energy loss is much higher than energy transmitted during the resonating process. In this research, we attempted to improve the matching of atoms at the interface of AlNoD by doping AlN lattice with boron atoms. The shrinking of the lattice may allow more atoms are aligned at the interface. Moreover, a method of coupling single crystal AlN on single crystal diamond is proposed. Such a coupling can maximize the signal-to-noise ratio of the resonating AlNoD at the same time minimize the insertion loss of the SAW filter.

Key words: SAW filter, diamond film, AlN, boron doping.

Diamond SAW Filter with ZnO Vibration

Piezoelectric material (e.g. ZnO) coated diamond film has been perceived as a superior SAW filter (vibrator or resonator) than conventional designs [2]. This is because diamond with its unsurpassed rigidity can boost Rayleigh (surface) wave at the interface so the signal frequency can be increased significantly. Moreover, due to the extreme thermal conductivity (e.g. >1000 W/mK) of diamond, the coupling heat generated from the interdigital transducer (IDT) can be dissipated fast so the SAW filter may be operated at high power (e.g. >10 W).

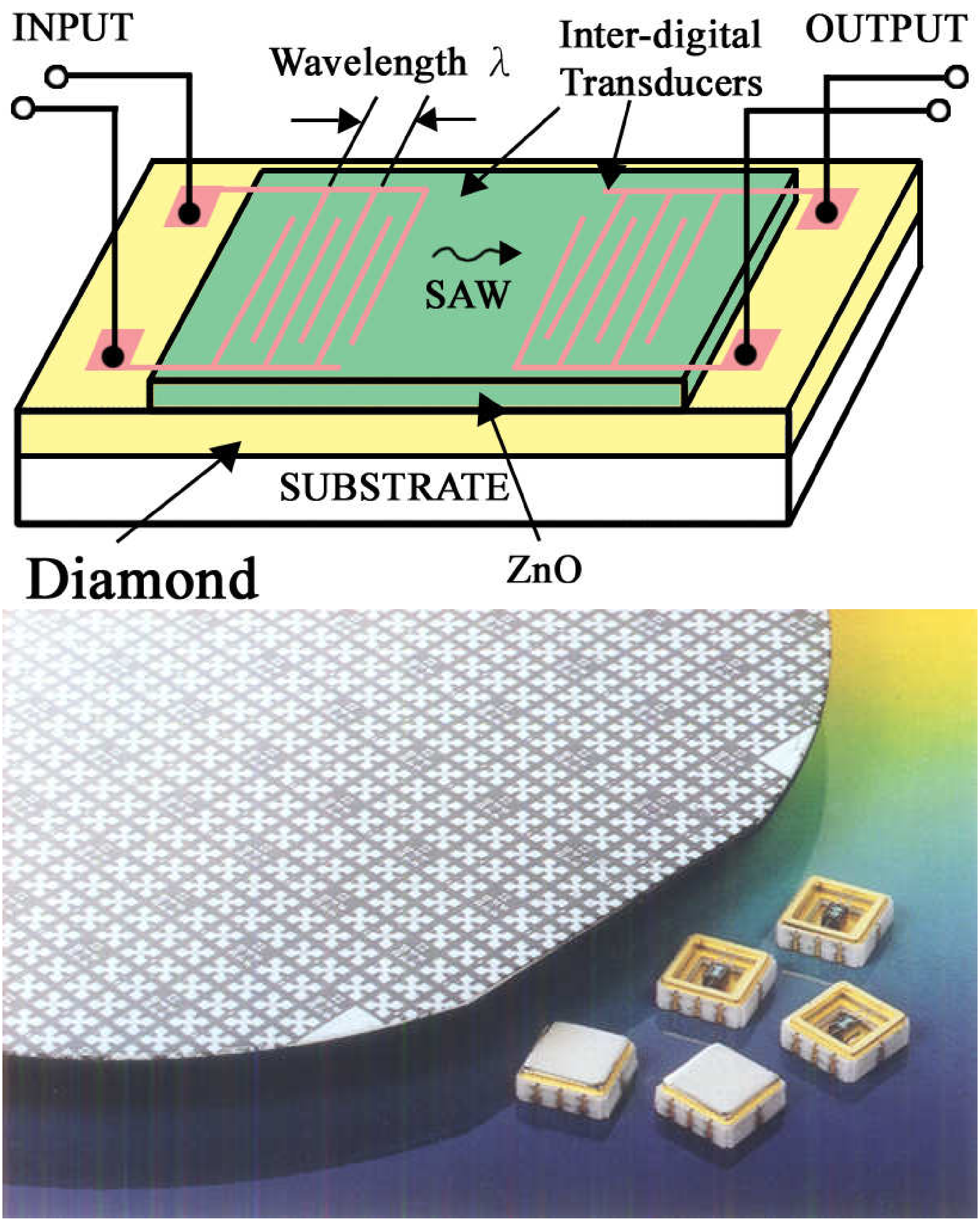

Fig. 1: The design and appearance of ZnO/diamond SAW filters (Sumitomo Electric Brochure).

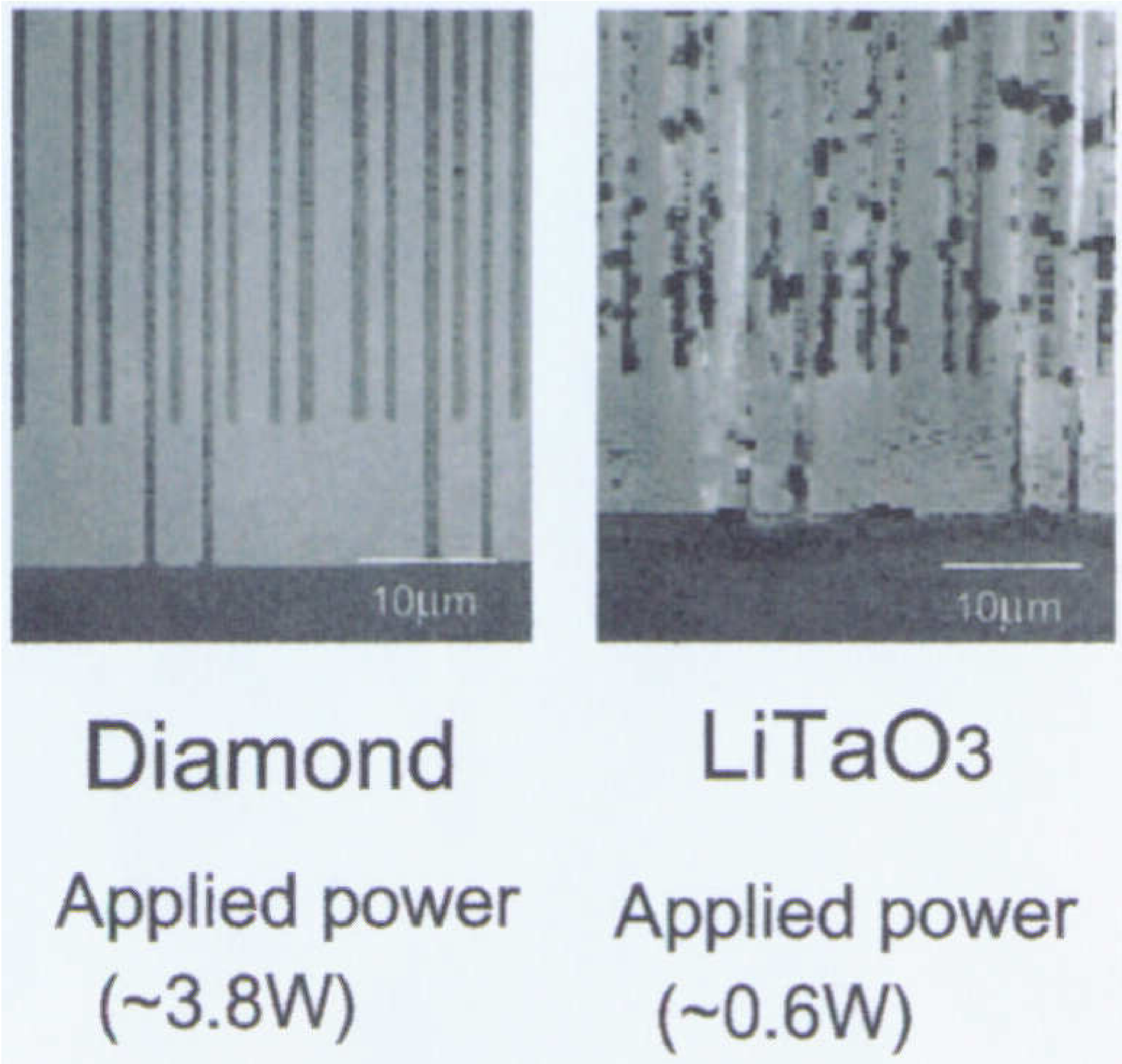

Fig. 2: The cooling effect of diamond substrate to avoid the melting down of aluminum IDT when the filter was operated at high power (Sumitomo Electric brochure).

Diamond on Lithium Niobate

ZnO has a low sound velocity that does not match well with the high acoustic speed of diamond. As a consequence, non-spherical vibrations at the interface are formed and the eccentricity of the atomic movement may accumulate along the path of wave propagation. Due to the mechanical drag of ZnO on diamond during the wave motion, the inharmonic noise is compounded so the resonating signal becomes unclear. Moreover, ZnO is typically formed by vapor deposition (e.g. sputtering) with microscopic grains. The piezoelectric effect is dampened by the large amount of grain surfaces and other defects. In addition, the bonding between ZnO and diamond is weak, so the transmission of vibration in ZnO to diamond, and vice versa, is ineffective. Consequently, most energy is lost as wasted heat.

In order to improve the filtering result, diamond film may be deposited on a single crystal resonator (Sung, Chien-Min, US Patent 6,814,130, filed on Oct. 19, 2001, and US Patent 7,011,134 filed on Apr. 22, 2003), such as lithium niobate, LN ($LiNbO_3$) that is a common vibrating film for SAW filters used in mobile phones [8]. But the diamond film deposition temperature is typically above 800℃ that can vaporize Li atoms in LN, so a process of low temperature (about 600℃) was adapted. The diamond formed was nanocrystalline with ample graphitic (sp^2) bonds. As a result, the hardness and young's modulus are less than half of that for pure diamond. However, if Ar is used instead of H_2 as the carrying gas for methane, uniform nano grains of diamond that is voided with graphitic bonds can be formed as Argonne National Lab demonstrated years ago.

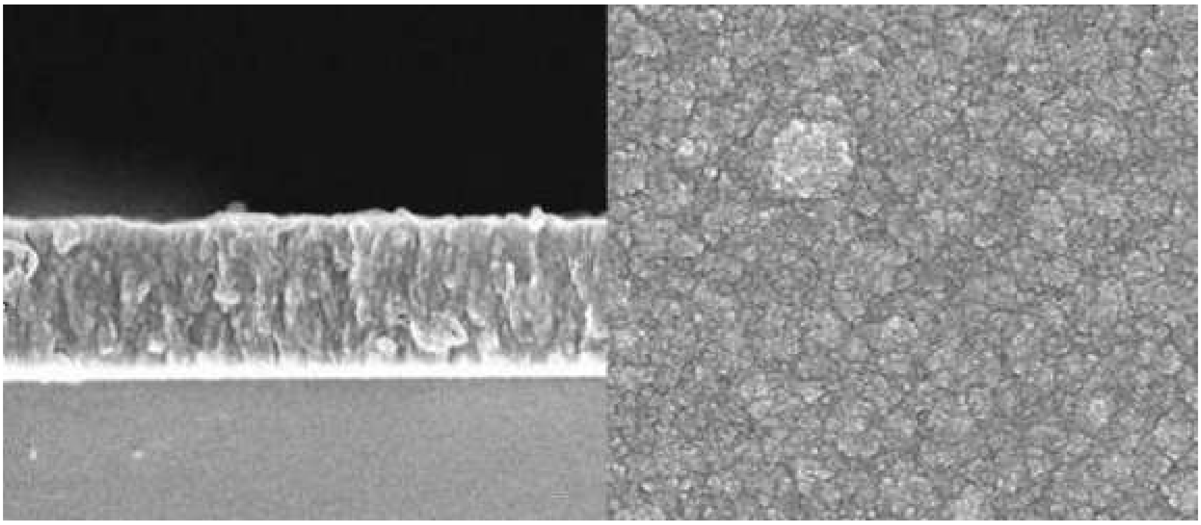

Fig. 3: The SEM micrographs of the top view and the cross section of the nano diamond film deposited on a lithium niobate wafer [14].

The Ideal Diamond SAW Filter

All oxide piezoelectric layers are ionic so the breakdown field is limited. As a consequence, the spacing of IDT cannot be tight as electrical leakage may occur. Moreover, oxides are highly thermal insulating, so the cooling effect of diamond is compromised. Furthermore, oxides are notoriously difficult to bond firm with diamond film. The faithful coupling between oxide layer and diamond film for effective transmission of SAW is therefore not possible.

As the ultimate SAW filter, hexagonal diamond is dream material. The piezoelectric hexagonal diamond has the same sound speed of cubic diamond and it is an intrinsic heat spreader. The next best piezoelectric material is würtzite BN (w-BN) that is the counterpart of cubic boron nitride. W-BN has a tight lattice so it can minimize the mismatch when it adheres to diamond. However, w-BN is hard to form, also its piezoelectric effect is weak.

Würtzite BN and würtzite AlN are isostructural solid solution. AlN is relatively easy to form on diamond, e.g. by sputtering or CVD. By replacing Al for B atoms in the same crystal structure, the lattice of AlN is tightened so its lattice matching with diamond improves. Boron doped AlN has a higher thermal conductivity and also with a higher breakdown field than any oxide piezoelectric material. These features allow using submicron spacing of Al IDT. However it is preferable to use a refractory metal (e.g. Ti) for making IDT of higher thermal stability. Refractory metals can bond firmer with BN (e.g. forming TiB_2 and TiN) or diamond (e.g. forming TiC) so the energy loss at the interface can be minimized.

Table 1: The Thermal and Electric Endurance of Semiconductors

Material	Thermal Conductivity (W/mK)	Break-down Field (MV/cm)
Si	150	0.3
SiC(4H)	500	3
GaN	130	5
Diamond	2400	10

A diamond SAW filter with AlN piezoelectricity fitted with tight IDT may attain a resonating frequency higher than 20 GHz. The IC processing compatibility of such a design would make diamond SAW filters a prime candidate of future high frequency communication devices. For example, diamond SAW filter can be mounted on the common platform of the future semiconductor-on-diamond (SOD) to form an extreme system-on-chip (SoC) that can process and transmit MW or even RF.

Table 2: The comparison of sound velocities among piezoelectric materials and diamond

Material	Rayleigh Wave Velocity (Km/sec)	% of Diamond Speed
ZnO(sputtered)	2.60	14
LiNbO3(64Y)	4.74	25
GaN(MOCVD)	8.77	47
AlN(Sputtered)	10.40	55
Diamond(CVD)	18.78	100

GaN data calculated from AlN
Diamond data referred from [13]

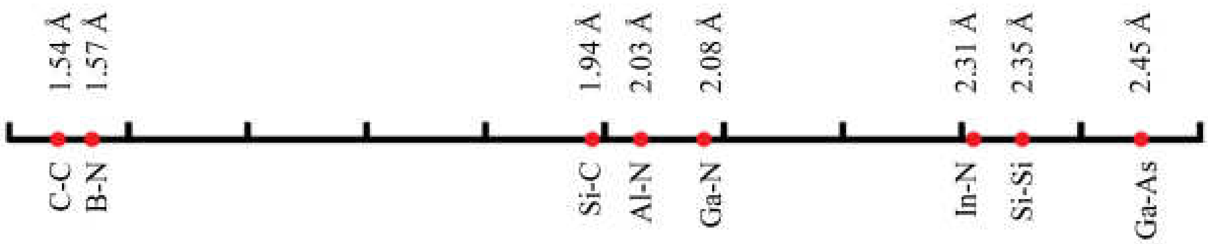

Fig. 4: The size scale of relevant semiconductors.

(Al,B) N Deposition

Boron doped AlN can be sputtered conveniently onto the surface of a polished diamond film. The boron doping can shrink AlN lattice to make it closer to diamond. Moreover, (Al,B) N film is stiffer than AlN film so a higher acoustic wave velocity is expected.

In order to increase further the lattice matching and also the adherence at the interface, boron doped diamond film may be used as the substrate. In this case, the expansion of diamond lattice and the tightening of AlN lattice can increase the amount of matching atoms across the interface.

The solid solution of (Al,B) N was formed on the surface of a CVD diamond film maintained at 200℃ by magnetron sputtering of both hBN (RF) and Al (DC) targets in a vacuum atmosphere that contains a mixture of nitrogen and argon. The diamond film (20 microns) was deposited by a HFCVD system onto a silicon wafer. The grown surface was polished to reach a surface smoothness of about 1 nm Ra. The diamond film substrate for this research was provided by Kinik Company.

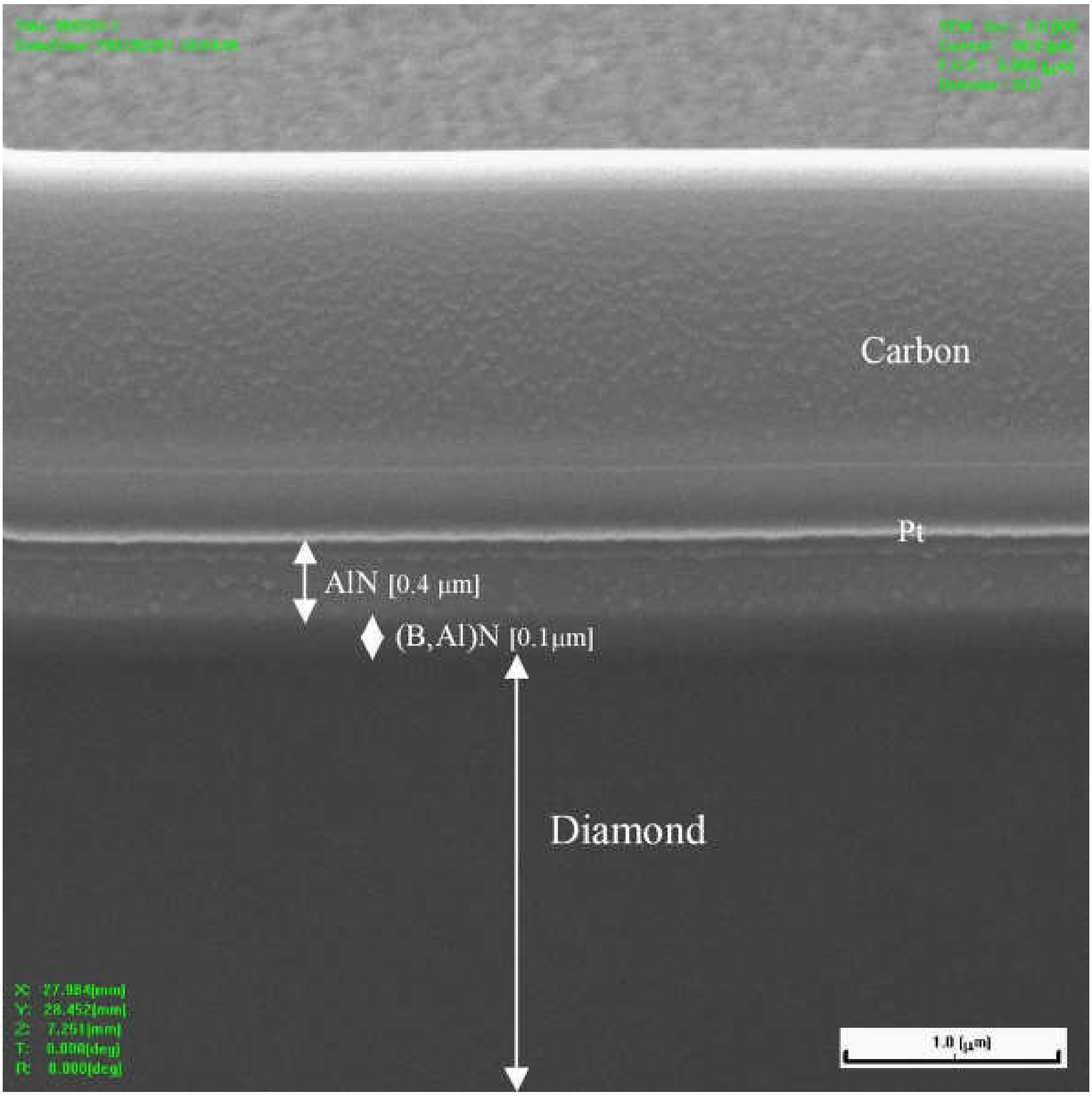

Fig. 5: SEM micrograph that shows the buffer layer (Al,B) N between diamond film and AlN layer.

It was observed that the B content in the sputtered film increases with the increasing RF power. Moreover, the increase of B was due to the replacement of Al in the AlN dominating lattice (wurtzite).

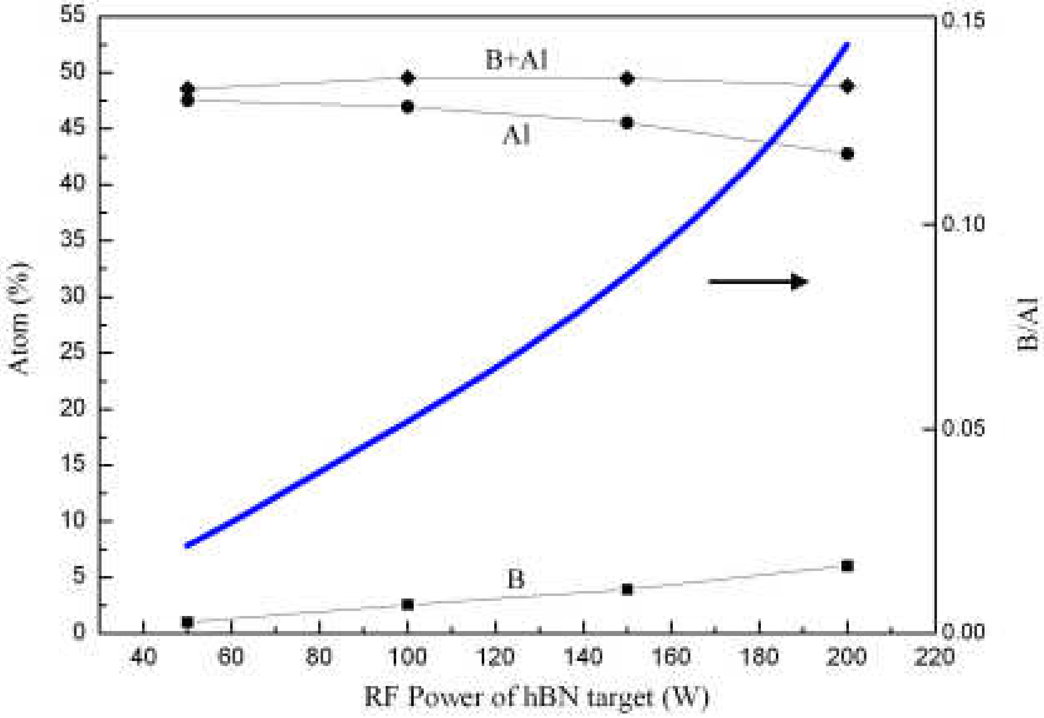

Fig. 6: XPS data of Al, B contents in the deposited film with AlN matrix as a function of RF power of the puttering. During the experiment, about 40% nitrogen atoms in AlN lattice were replaced by oxygen. Note that B atoms are incorporated at the expense of Al atoms in the lattice of AlN [22].

It is observed that a significant reduction of lattice size accompanied the replacement of Al by B atoms. However, because the flakes of AlN are larger in a-direction than in c-direction, the shrinkage along the basal planes is more dramatic than that between them.

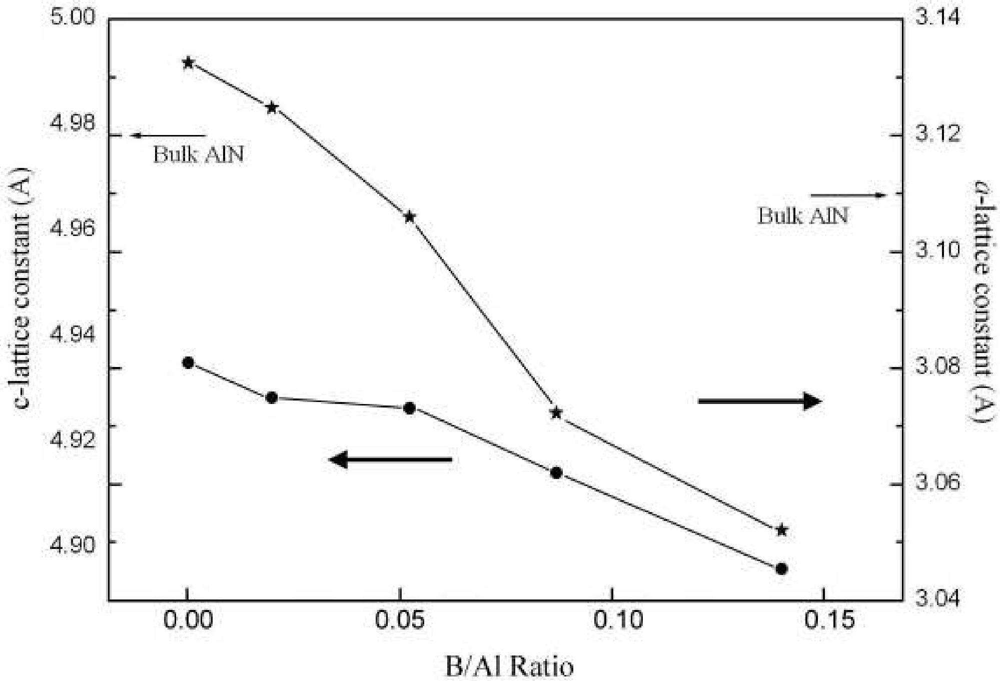

Fig. 7: The lattice constant as a function of boron content in AlN.

AlNoD SAW Filter

An AlNoD wafer provided by Kinik was fabricated into a resonator at Tai Saw, a major SAW filter maker in Taiwan. The Al IDT was formed by using the same mask that produced quartz resonators. The measured peak frequency for resonating quartz was determined to be 434.42 MHz.

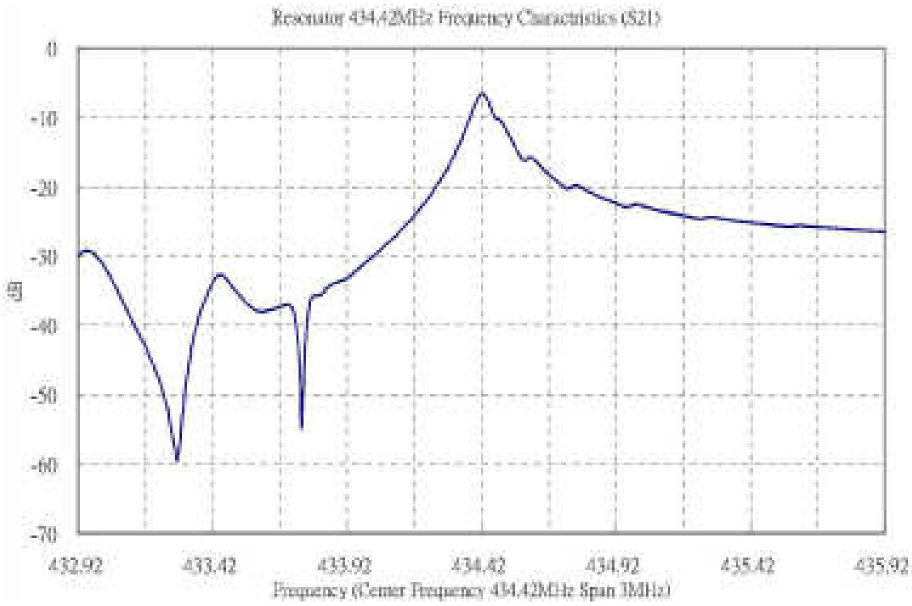

Fig. 8: Resonating spectrum of quartz.

The same mask that produced the above spectrum was used to fabricate AlNoD. The FWHM of the rocking curve for the sputtered AlN was 3.129 degree. The resonating spectrum demonstrated the dramatic increase of the frequency to over 1 GHz.

Fig. 9: The resonating spectrum of AlNoD.

An AlNoD wafer was also sent to Temex in France for the fabrication of a resonator with a tighter IDT of about 1 micron. The rocking curve of the sputtered AlN was 9.882 degrees. The resonating frequency was found to be about 5 GHz with a Q value of about 400. The calculated acoustic wave speed was 9.14 Km/sec for the composite structure.

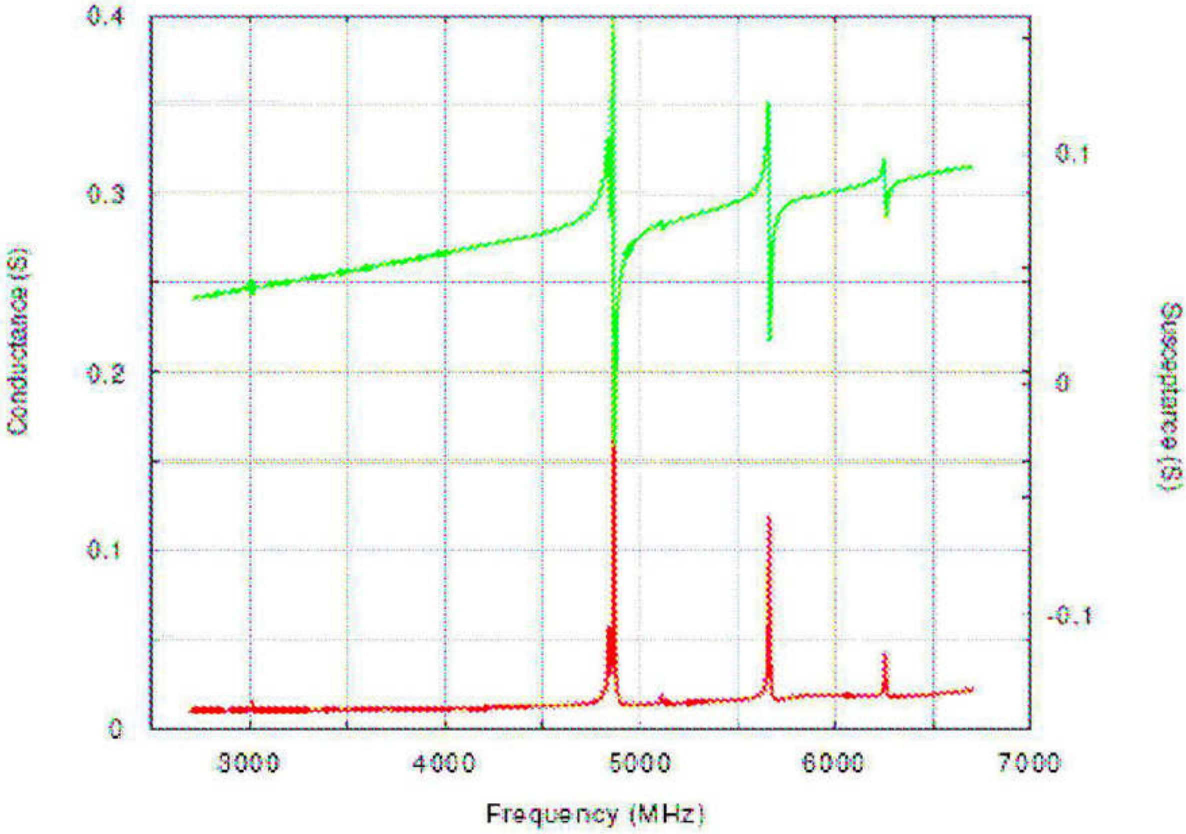

Fig. 10: The resonating spectrum of AlNoD with the peak at 4.865 GHz.

The adherence of sputtered AlN on diamond film is weak. As a result, the insertion loss during the energy transfer is large. One way to overcome the bonding at the interface is to deposit Ti on diamond and TiN on Ti. After then, AlN can be firmly attached on TiN [15].

Reverse Casting of Diamond Film on AlN

GaN is another piezoelectric material that may be used to construct a diamond SAW filter. Diamond film was used as the substrate to deposit GaN by MOCVD. The film so formed was polycrystalline due to the large lattice mismatch between relaxed GaN and tightened diamond.

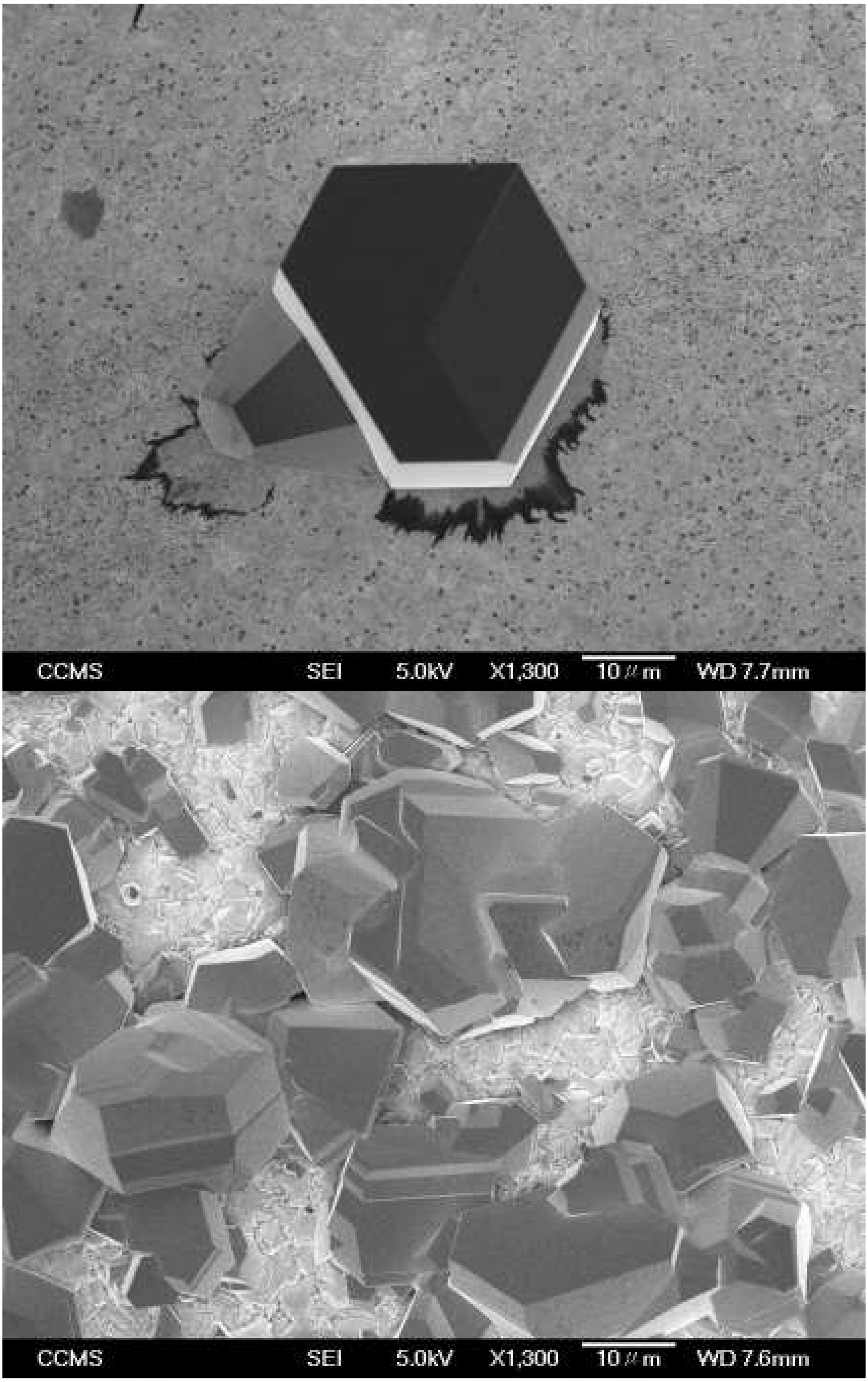

Fig. 11: GaN deposited on polished polycrystalline diamond film. Note some crystals show basal plane alignment of GaN along the wafer surface.

In order to overcome the problem of lattice mismatch, GaN formed on sapphire (e.g. for making LED) may be bonded to polished diamond film by brazing and the sapphire substrate removed (e.g. by laser splitting) afterwards.

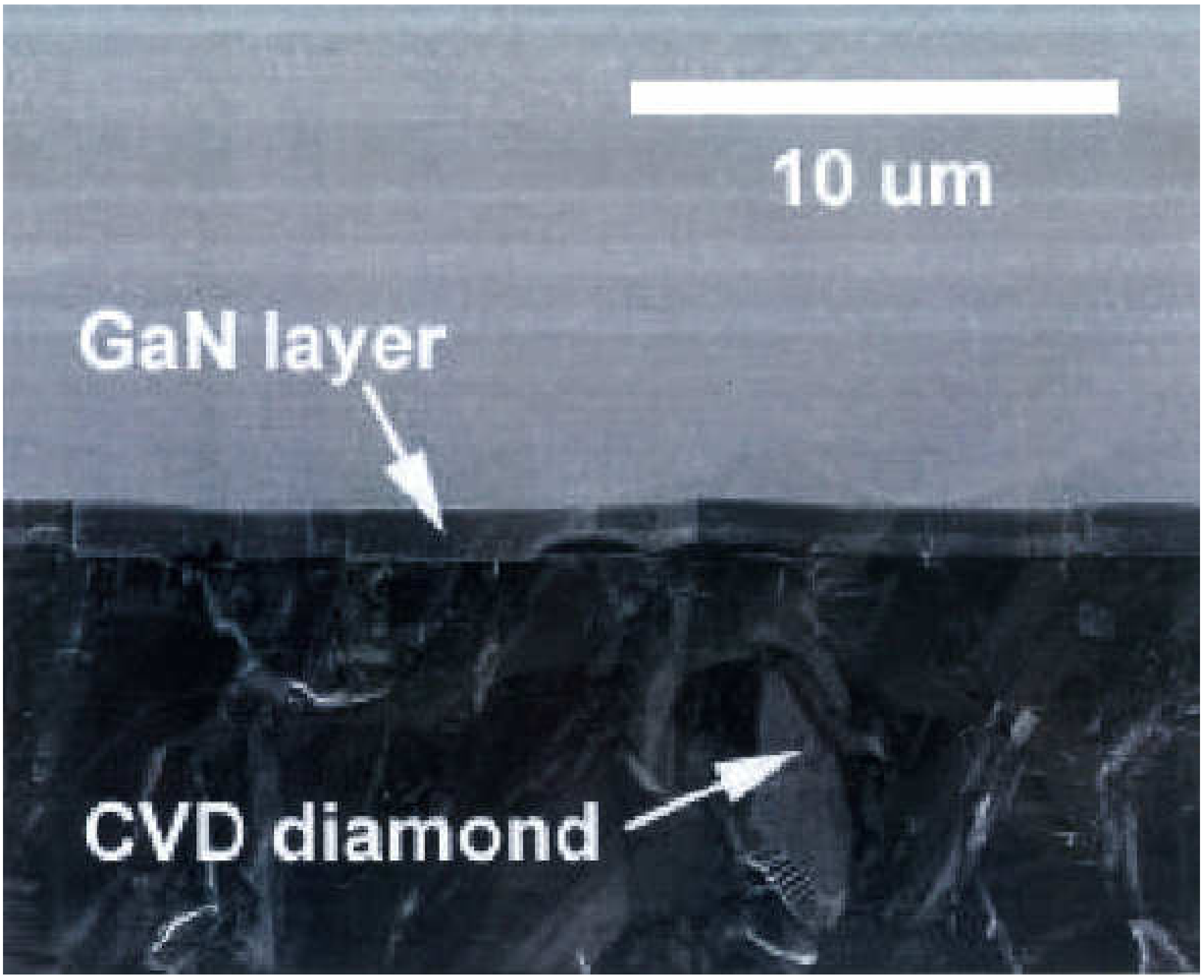

Fig. 12: The cross section of GaN on diamond (Group 4 Website).

AlN is the common buffer layer for GaN LED with sapphire as the major substrate. Instead of coating diamond film with microscopic AlN, diamond film can be deposited onto AlN or GaN wafer. In this case the piezoelectric layer is a polycrystalline AlN or a single crystal GaN. However, if the above substrate of GaN on AlN or sapphire can be used to deposit AlN again (e.g. by MOCVD), the AlN so formed can be a single crystal. The perfection of AlN single crystal can be facilitated by grading the composition of GaN to AlN in such a way that Al to Ga ratio in the mixed crystal is increasing. As GaN and AlN form a solid solution with no limitation, AlN lattice can follow the guidance of GaN lattice. The AlN single crystal so formed would be the best piezoelectric layer as it would not attenuate the wave propagation. Moreover, if the AlN can be graded with the addition of boron atoms, the tightened lattice of (Al,B) N is an excellent substrate for growing single crystal diamond film with hetero-epitaxy, particularly, if the diamond lattice is opened up by doping with boron atoms. If both (Al,B) N and diamond are single crystal, the SAW can be transmitted with the minimal loss of energy. Moreover, the signal to noise ratio would be the most clear due to the elimination of most grain boundaries.

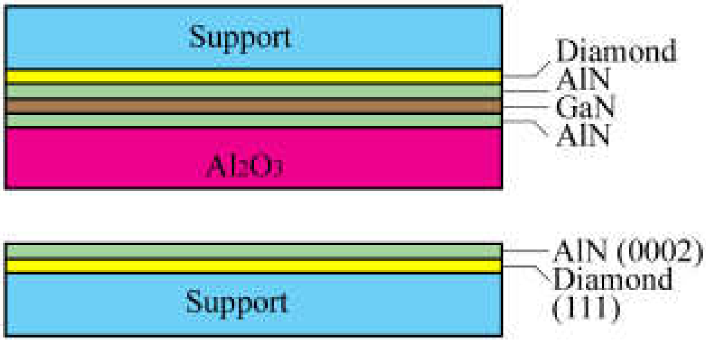

Fig. 13: The schematic of growing single crystal AlN on GaN and the subsequent deposition of diamond with hetero-epitaxy. After the removal of GaN, the AlN on diamond duplex is the most efficient SAW filter system conceivable (Sung, Chien-Min, US Patent 7,095,157 filed on Nov. 8, 2004).

Conclusion

AlNoD can be the ideal substrate for fabricating high quality SAW filters or resonators. The improved attributes include high frequency (>20 GHz), high power (>10 W), small size and IC process compatibility. AlNoD can be integrated with SOD to form a superior SoC that may obsolete current designs of SoC.

The most desirable AlNoD can be fabricated by using an LED system with GaN on sapphire. A single crystal AlN may be deposited on GaN with chemical gradation from Ga to Al. The AlN so formed can be doped with boron. Subsequently boron doped diamond can be grown on the boron doped AlN. The diffused boundary between piezoelectric AlN and diamond can preserve the most of the wave energy so the best result of SAW resonance can be achieved.

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