# CVD DIAMOND: THE EMERGING ELECTRONIC MATERIAL

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## Abstract

Diamond exhibits several remarkable properties that makes it a highly desirable material for passive and active electronic device applications. The critical properties of interest in this context include the wide band gap ( 5.45 eV), exceptional thermal conductivity ( 20 W/cm° K ), high electrical resistivity ( $10^{16}$ Ohm cm) and the high elastic modulus ( 10.35 * $10^{12}$ Dynes/cm$^2$ ) of diamond. Diamond based semiconductor devices should be able to operate at high temperatures, at high frequencies and at high power densities. In addition the wide band gap should also make diamond significantly more immune to the effects of ionizing radiation as compared to other common semiconductors. The ability to synthesize thin diamond films utilizing plasma enhanced CVD techniques has enhanced the prospects for diamond based electronics. In this paper we will discuss some of the potential passive and active electronic applications of thin, polycrystalline diamond films and discuss the current status of the diamond film synthesis technology.

## Introduction.

The ability to synthesize diamond films at relatively low temperatures ( <1000°C) and pressures ( 20 to 200 Torr) using plasma enhanced CVD techniques offers the opportunity for using these films in electronic applications. Table 1 shows selected electronic properties of Silicon, Gallium Arsenide and Diamond.

|  | Silicon | GaAs | Diamond |
|---|---|---|---|
| Thermal Conductivity (W/Cm-K) | 1.45 | 0.46 | 20 |
| Band Gap (eV) | 1.124 | 1.43 | 5.45 |
| Relative Dielectric Constant | 11.7 | 13.8 | 5.5 |
| Lattice Electron Mobility (V/cm$^2$) | 1350 | 8800 | 1900 |
| Lattice Hole Mobility (V/cm$^2$) | 480 | 400 | 1600 |
| Breakdown Electric Field (V/cm) | 3.00E+5 | 3.50E+5 | 1.00E+7 |
| Maximum Electron Velocity (cm/sec) | 1.00E+7 | 1.10E+7 2.50E+7 | 2.70E+7 |
| Fastest Switching Speed[1] [5/Eb*$v_s$ (sec) (5V device)] | 1.67E-12 | 5.71E-13 1.30E-12 | 1.85E-14 |
| Maximum Operating Temperature[2] (C) | 225 | 470 | 1900 |

[1]The switching speed is for the minimum length transistor determined from the breakdown field. The two numbers for GaAs arise due to the fact that the switching speed of GaAs is higher at low fields (currents).

[2]This calculation defines the upper temperature limit of operation as the point when a substrate doping level of 1.0E14/cc is overwhelmed by thermal carriers.

Table 1 Selected Electronic Properties of Silicon, GaAs and Diamond

From Table 1 it is clear that diamond based devices offer many significant advantages as compared with silicon and GaAs based devices including higher breakdown voltages, superior power handling capabilities and the potential for very high temperature operation. A more rigorous approach for comparing various semiconductors with regard to desirable device related properties is the use of several figures of merit that have been developed for this purpose. These figures of merit utilize the appropriate materials properties of the semiconductors that have a bearing on the performance characteristics of devices and circuit elements. The Keys figure of merit [1] is given by:

$$KFM = \lambda \left[ c\, v_s / 4\, \pi\, \varepsilon_r \right]^{1/2}$$

where $\lambda$ is the thermal conductivity, c is the velocity of light, vs is the scattering limited velocity of charge carriers and $\varepsilon_r$ is the relative permitivity of the semiconductor. This figure of merit is an indicator of the thermal limitation of the material on its high frequency electrical performance.

The Johnson [2] figure of merit, which is an indication of the frequency power product of the semiconductor is given by:

$$JFM = E_M\, V_s / 2\, \pi$$

where $E_M$ is the peak electric field strength at avalanche breakdown.

Using the peak electric filed strength at avalanche breakdown as the critical material parameter Shenai et.at.[3] have developed a new set of figures of merit as follows:

$$QF_1 = \lambda\, \sigma_A\, ; \quad QF_2 = \lambda\, \sigma_A\, E_M \quad \text{and} \quad QF_3 = \sigma_A$$

where $\sigma_A$ is the drift region conductance per unit area and is given by:

$$\sigma_A = \varepsilon_s\, \mu\, E_M^3 / 4\, V_B^2$$

where $\mu$ is the low field drift mobility of the charge carriers in the drift region, $V_B$ is the avalanche breakdown voltage and $\varepsilon_s$ is the permitivity of the semiconductor.

The figures of merit due to Shenai et.al. are considered to be more appropriate for the evaluation of semiconductor materials for power device applications where the maximum electric field strength at avalanche breakdown is the more important parameter whereas the Keys and the Johnson figures of merit better relate to evaluating materials for use in transistors for high speed electronics and for microwave and millimeter wave applications.

Using appropriate values for the various parameters, the figures of merit for silicon, gallium arsenide, silicon carbide and diamond are shown in Table 2. The numbers have been normalized to those of silicon.

From the comparison of the figures of merit it is clear that wide band gap materials have superior electronic attributes with diamond up to a million times less susceptible to ohmic heating than silicon. Furthermore diamond appears to be better suited for both high performance ( high speed) and high power transistors than the other semiconductors.

| Material | KFM | JFM | $Q_{F1}$ | $Q_{F2}$ | $Q_{F3}$ |
|----------|-----|-----|------|------|------|
| Si | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Ga As | 0.5 | 6.9 | 2.42 | 2.59 | 7.8 |
| SiC | 5.8 | 1138 | 297 | 2400 | 90 |
| n-Diamond | 32 | 8206 | $5.3 \times 10^4$ | $1 \times 10^6$ | $4 \times 10^3$ |
| p-Diamond | 32 | 8206 | $4.2 \times 10^4$ | $8 \times 10^5$ | $3.2 \times 10^3$ |

Table 2. Comparison of the Keys (KFM), the Johnson (JFM) and the Shenai et.al. ($Q_{F1}$, $Q_{F2}$ and $Q_{F3}$) figures of merit for selected semiconductors.

## CVD Diamond Film Synthesis - Current Status

The significant potential of diamond as an electronic material is quite evident from the analysis presented above. The ability to realize the expected superior performance from diamond based devices is based on the ability to synthesize high quality materials, the ability to dope the films and the ability to make contacts to the films. In this section we present a brief discussion of the current status of CVD diamond technology with respect to factors such as the reliability and the reproducibility of the synthesis processes, the physical properties that have been measured and their applicability to the use of these films in electronic applications.

Diamond films of thicknesses ranging form several thousand angstroms to hundreds of microns have been synthesized using a variety of approaches including the use of DC glow discharge, microwave excited plasmas and thermal decomposition techniques using hot filaments. These films are polycrystalline in nature and are typically characterized by a high defect density in the forms of twins, stacking faults and dislocations.

An important issue with respect to the growth of diamond films on a variety of substrates is the difficulty of nucleating these films. There appears to a barrier to nucleation and a variety of approaches to promoting nucleation have been investigated. In general it is found that the surface of the substrate has to be abraded with a suitable abrasive such as diamond dust to create local regions of surface damage which promote nucleation.[4] A recent approach for promoting diamond film nucleation without damaging the substrate has been discussed.[5] Based on these results it is possible to synthesize diamond films with insignificant amounts of garphitic or non diamond bonded carbon based impurities as contaminants. The bonding state of carbon atoms in these films is best characterized by the use of Raman spectroscopy. Figure 1 shows a typical example of a Raman spectrum obtained from a natural diamond crystal compared with a Raman spectrum obtained from a diamond film synthesized in the laboratory using the PECVD approach. The strong Raman shift at 1333 cm$^{-1}$ is indicative of diamond or sp$^3$ bonding between carbon atoms. The two spectra are essentially indistinguishable from each other attesting to the fact that high quality diamond films, with all the superior attributes of this material, can be fabricated in an industrial environment.

The polycrystalline nature of these films is shown in Figure 2 which includes scanning electron micrographs of the surface structure of several diamond films deposited on silicon wafers. The structure of these films can be controlled by controlling process variables including the plasma chemistry, the gas pressure and the substrate temperature. Figure 2 shows examples of the range of microstructures that are possible for CVD diamond films. The grain sizes range from many microns in diameter down to several hundred angstroms. The deposition technology has been developed to a sufficient degree that thin diamond films can be uniformly deposited over 4 inch diameter substrates, substrate dimensions that are approaching practical dimensions for electronic applications.[5]
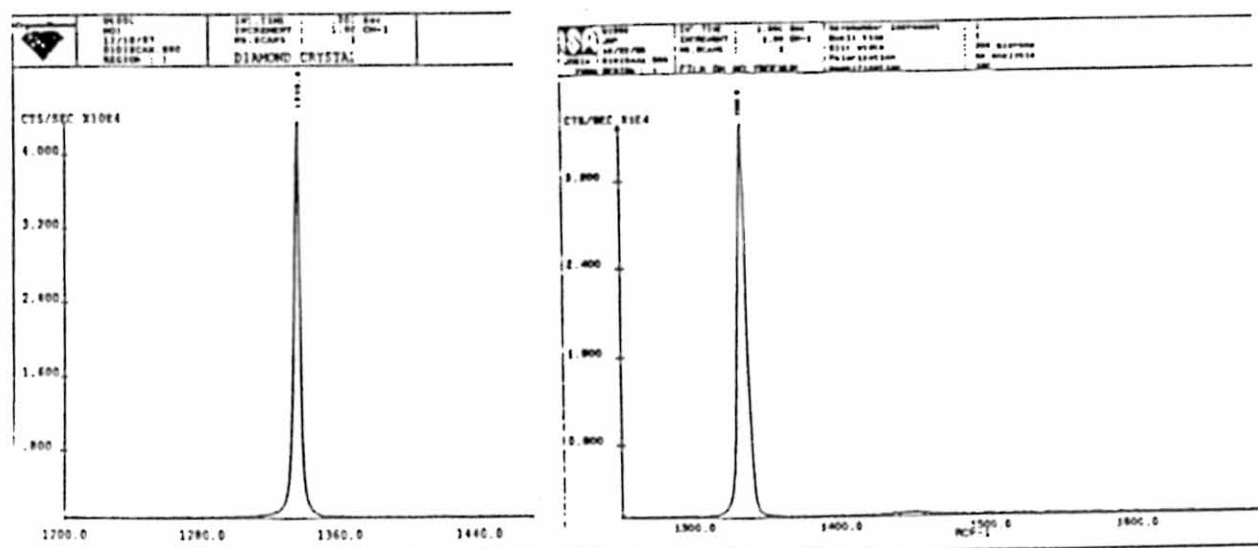
Figure 1. Raman spectra from a natural diamond crystal (left) and a plasma synthesized diamond film (right). The sharp Raman peak at 1333 - 1335 wavenumbers is indicative of diamond ( $sp^3$) bonding in the material.
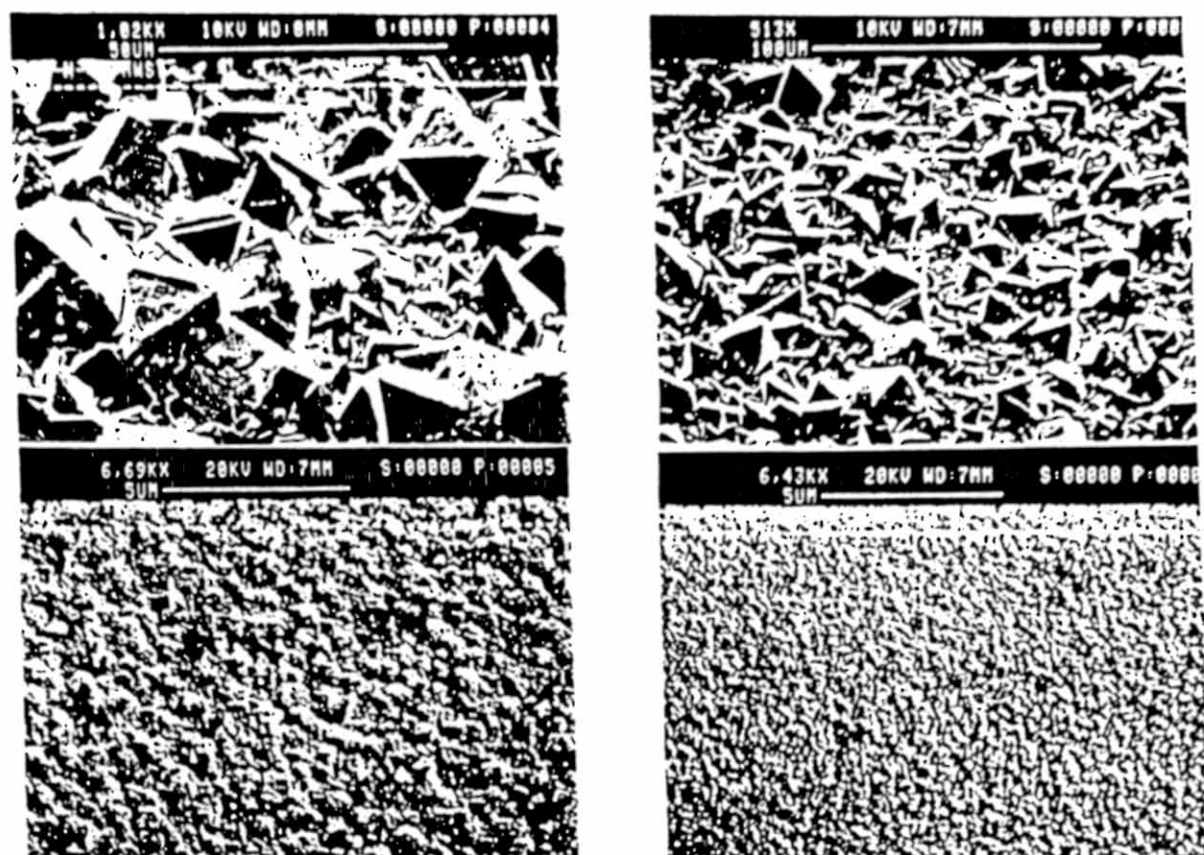


Figure 2. Examples of the range of grain sizes achieved in CVD diamond films.

# Electronic Applications of Diamond films

Based on the current status of the technology of diamond film synthesis the primary applications of these films reside in their use in passive electronics. However by controlling the structure of the polycrystalline diamond films to minimize the effects of grain boundaries on transport properties, active electronic devices may be fabricated. For realizing the ultimate potential of diamond as an electronic material single crystal diamond growth technology has to be developed. Some selected applications of diamond films in passive and active electronics are shown in Figures 3 a and b. The key process and property requirements for addressing the various applications are also shown in the figure. Some of these applications will be discussed in greater detail below.

Figure 3 a. Selected passive electronic applications of CVD Diamond films

| Application | Range of Applications | Technical Requirements |
|---|---|---|
| Heat Sinks, Thermal management | Power device packaging, Heat dissipation from laser diodes, multichip packages and printed circuit boards | Thick diamond films ($>10\mu M$); high growth rates; low temperature synthesis |
| Dielectric Films | Interlevel dielectrics in silicon circuits, radiation hard structures | Thin films ($<0.2\ \mu M$); high nucleation density |
| Passivation, Surface protection | Passivation, corrosion and scratch protection of circuits, photomasks | High quality, pinhole free films; low temperature synthesis |
| X-Ray lithography | Membranes for X-ray lithography masks. | Free standing diamond films in tension, absorber deposition and patterning. |
| Silicon on Insulator Structures | High speed, high density, radiation hard silicon devices and circuits, Bi CMOS structures. | High resistivity, high thermal conductivity films |

Figure 3 b. Selected active electronic applications of CVD Diamond films

| Application | Range of Applications | Technical Requirements |
|---|---|---|
| Polycrystalline diamond devices | Thin film transistors FET'S, Picosecond high voltage optoelectronic switches | Oriented polycrystalline films, doped films, contacts |
| Single crystal diamond devices | High temperature, high speed radiation hard devices | Heteroepitaxial growth of single crystal diamond, doping, contacts. |

## Dielectrics, Passivation and Surface Protection

The requirements for the use of diamond films as dielectric films in conjunction with silicon structures and for passivation and surface protection are generally similar. These applications require thin films ( < 1 μM) of high quality diamond, free of pinholes, deposited over large area
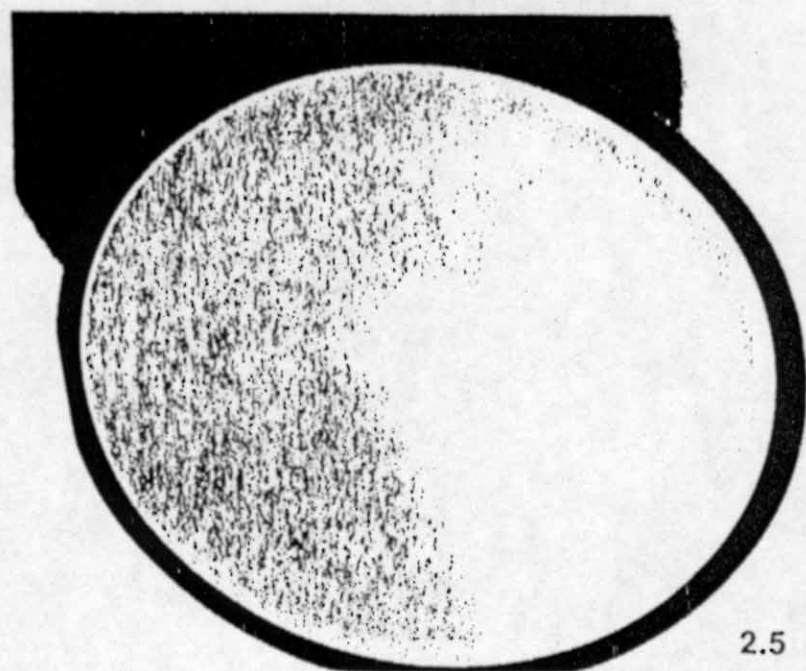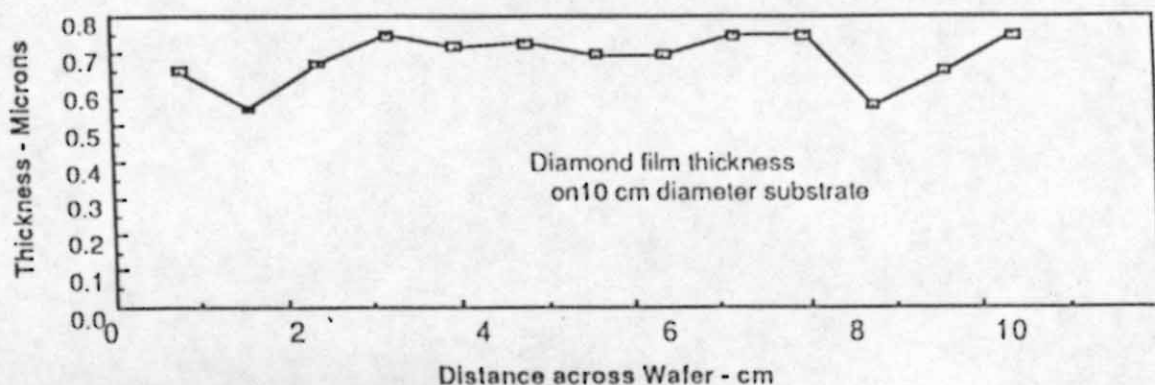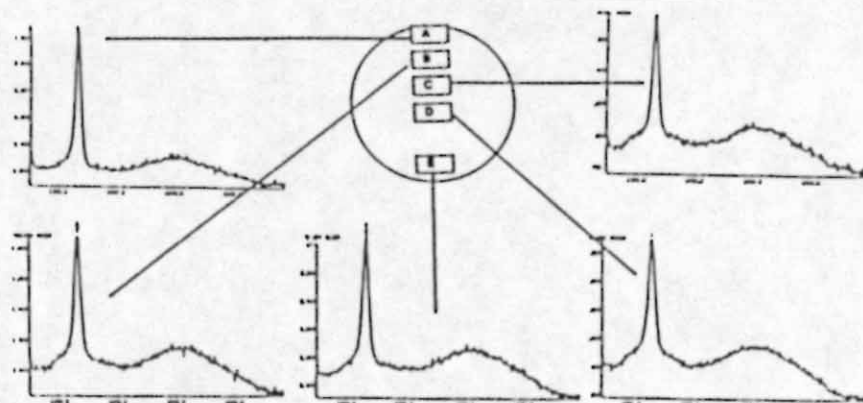


Figure 3. Example of a diamond film deposited on a 10 cm (4 inch) diameter silicon wafer. The uniformity of thickness distribution of the film across the wafer is shown in the top figure. The positional dependance of the Raman spectrum of the film is shown below.

wafers with good thickness and compositional uniformity. Figure 3 shows an example of a thin diamond film deposited on a 10 cm diameter silicon wafer. The uniformity of the film thickness and the uniformity of the film composition as determined by Raman spectroscopy are also shown in the figure.

For commercial applications whereby diamond films are combined with silicon wafers for use as dielectrics and as protective overcoats, the process and the equipment have to be scaled to achieve uniform diamond deposition over 5 and 6 inch diameter silicon wafers. For the use of diamond films as protective overcoats on fabricated silicon wafers, comprised of active and passive elements, dielectric films, contacts and interconnects, it is necessary that diamond film synthesis be achieved at temperatures below ~ 400°C to prevent destruction of the circuits due to diffusion of contact and interconnect metallization. Although there have been some early indications that diamond synthesis can be achieved at such low temperatures,[6] the technology requires further development prior to commercialization.

## Silicon on Insulator Structures using Diamond

One of the most attractive applications of diamond films is their use as insulators beneath thin single crystal silicon films in silicon on insulator structures. The ability to create thin high quality silicon single crystal films on insulators has far reaching implications in semiconductor technology. In order to form single crystal silicon films on insulators the normal approach has been one of heteroepitaxy of silicon on an appropriate insulating single crystal substrate such as sapphire. In order to achieve SOI structures incorporating diamond films as insulators the traditional approach would require that single crystal diamond films be grown followed by the heteroepitaxial growth of silicon films on the diamond films. There are no currently proven approaches available for the heteroepitaxial growth of single crystal diamond films. In addition the very large lattice mismatch between silicon and diamond (65%) would preclude heteroepitaxial growth of silicon on diamond. Consequently in order to advantageously use the exceptional insulating and thermal conductivity characteristics of diamond films, approaches for the use of polycrystalline diamond films in conjunction with single crystal silicon films have to be developed.



Single crystal Silicon ( 2 μM)

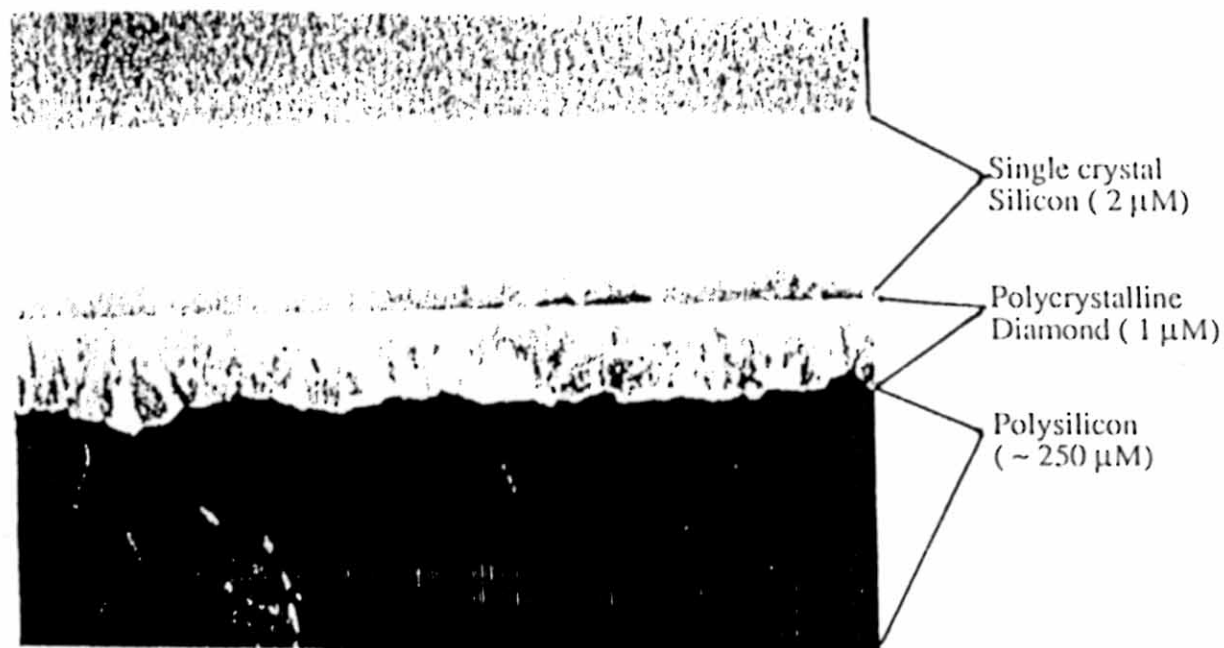Polycrystalline Diamond ( 1 μM)

Polysilicon ( ~ 250 μM)

Figure 4. Scanning electron micrograph of a silicon on insulator structure using diamond.

Such an approach is under development whereby polycrystalline diamond films are grown on single crystal silicon films which are homoepitaxially grown on single crystal silicon substrates. Following diamond deposition a thick polysilicon layer is grown on the diamond film and the original single crystal silicon substrate selectively removed by using appropriate etching agents [7].

Figure 4 shows cross sectional scanning electron micrographs of a silicon on diamond wafer demonstrating this process. The diamond film is backed up by a polysilicon film to provide the structural support for the thin silicon epitaxial layers and the thin diamond films. In Table 3 the potential advantages on this approach are compared with the two most developed SOI approaches.

Table 3. A Comparison of Silicon-on-insulator Technologies

| | SILICON ON SAPPHIRE | SIMOX | SILICON ON DIAMOND |
|---|---|---|---|
| Dielectric Constant | 4.5-8.4 (Sapphire) | 3.9 ( $SiO_2$) | 5.5 (Diamond) |
| Thermal conductivity | 0.3 | 0.014 | 20 W/ cm °K |
| Density of Interface States | $2*10^{12}$ | $8*10^{10}$ | Unknown |
| Electrical resistivity (ohm cm) | $10^{15}$ | $10^{14}$-$10^{16}$ | $10^{16}$ |
| Silicon Thickness | > 0.3 microns | > 0.1 micron | <.05 microns ? |
| Thickness of insulator | 15-20 mils | < 1 micron | <1 to >10 microns |
| Silicon Quality | Low mobility, high density of interface defects | potential for impurity contamination; high oxygen content | Potential for high quality |
| Manufacturing Cost | High (High capital cost) | Low Low | Potentially |

Some of the potential attractions of the incorporation of diamond films with silicon are as follows:

1. Very high speed integrated circuits can be fabricated because of the possibility of fabricating very thin silicon on insulator wafers. The basic approach should permit very high quality silicon since no heteroepitaxy is involved in the process.

2. Circuits, such as BiMOS circuits, that benefit from the superior thermal conductivity of the diamond insulator will perform better. Circuits and devices that are otherwise heat limited in order to achieve their full operational capability will benefit from these structures.

3. Due to the possibility of creating thin, high quality silicon layers on a superior insulator, circuits that are highly radiation tolerant and free from malfunctions due to latch up and soft errors can be fabricated.

## Active Electronic Applications

There has not been a significant amount of work reported on the electronic characteristics of polycrystalline diamond films. This can be attributed to the relatively recent origins of this technology and the general difficulty that has been experienced in growing thin films of diamond of

controlled and high quality. It has been demonstrated that diamond films can be doped with an acceptor such as boron by employing gas phase doping techniques [4]. Post growth doping of diamond has not been demonstrated to date. Solid state doping may not be feasible due to the expected low diffusion coefficient of donors and acceptors such as phosphorus and boron in diamond. There is no data on the diffusion coefficient of these elements in diamond films. However from the calculated values of the activation energy for self diffusion in diamond ( 9.1[8] eV vs. 3.6 to 5.1 eV [9,10] measured values for silicon) and the high activation energy for vacancy migration ( 1.7 to 1.9 eV [8] vs. 0.33 to 0.44 eV for silicon [11]) the diffusion coefficients for the expected donor and acceptor impurities are likely to be low. Doping by ion implantation has been attempted with limited degree of success. By using a suitable combination of low temperature implantation followed by annealing, substitutional doping has been suggested as being possible (12).

That diamond films can be doped in a controlled manner using *in situ* gas phase doping during diamond film synthesis is shown in Figure 5. The resistivity of a diamond film is plotted as a function of position from the boron source, a solid piece of boron. The boron was placed on one end of an undoped diamond film grown on a silicon wafer and a second diamond layer grown on the undoped film. Gas phase doping of the film was achieved as a result of the conversion of the boron into diborane and the transport of the diborane and the incorporation of boron in the growing diamond film. The fact that at these temperatures (~ 700°C) no solid state diffusion of boron occurs is shown by the high resistivity of the diamond films beneath the boron pellet. Low resistivity is observed immediately adjacent to the boron pellet with a monotonic increase in the resistivity with distance form the source, indicating that gas phase doping is occurring and that depletion of the gas borne source results in a reduction of the boron concentration of the film with distance from the source.
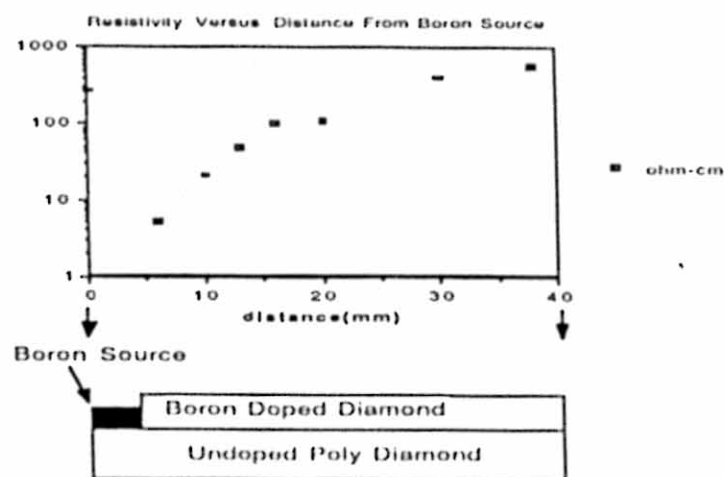
Figure 5. The effects of gas phase boron doping of diamond films. Top graph shows the resistivity of the film as a function of position from the solid boron source. The schematic illustration below shows the sample configuration. The monotonic doping dependence with distance from the source indicates the absence of a high density of donor defects that would impede p-type doping. The lack of doping underneath the boron source indicates that the diffusion coefficient of boron in diamond at the diamond deposition temperatures used ( ~ 700°C) is negligibly small. The film thicknesses in this experiment were 1500 Å for the boron doped diamond layer on top of a 3.0 μM thick of undoped diamond film. The resistance values have been calculated assuming a 1500Å thick film.

Both ohmic contacts and Schottky barriers have been made to CVD diamond films using metals such as Au and Al. Barrier heights of 1.13 eV have been measured and it has been shown that both static and small signal characteristics of the diodes are controlled by deep acceptor centers. The barrier properties have been reported to be essentially similar to those fabricated on natural diamond crystals [13]. An examination of the Si /diamond energy band diagram suggests that p+ silicon is a prime candidate for forming ohmic contacts to p type diamond. Ti/Au and Ta/Au have also been reported to form acceptable contacts. Based on the energy band diagrams of graphite/diamond and silicon carbide/diamond, both graphite and n+ silicon carbide are found to have work functions which are energetically in the middle of the band gap of diamond. This results in a Schottky barrier built in voltage on the order of 3.0 volts. The energy barrier to electrons in the silicon/silicon dioxide system is 3.0 volts. Having a high built in voltage is a very important criterion for the the device to operate at high temperatures.

As discussed above diamond films currently being grown are polycrystalline in nature. The use of polycrystalline diamond films for the fabrication of active electronic devices is contingent upon achieving the appropriate structure in the films in order to minimize the effects of grain boundaries. The impact of grain boundaries in diamond films can be minimized if controlled microstructure diamond films can be grown whereby the individual grains in the film are oriented preferentially. In such a case the grain boundaries will be normal to the film surface. It has been shown that by matching a set of major planes of the substrate with a set of planes of the overlying film, oriented, textured growth of films on lattice mismatched substrates is possible [14,15] It has been shown that textured polycrystalline diamond films can be grown on single crystal silicon substrates[16]. <011> textured films of diamond have been grown on {100} oriented silicon single crystal substrates. Large single crystal grains of diamond have either the {111}( lattice spacing 2.05 Å ) or the {200} (lattice spacing 1.78 Å ) planes matching with {022}( lattice spacing 1.92Å ) planes of silicon with a misfit of 7 to 8%. Figure 6 shows a transmission electron micrograph and corresponding selected area electron diffraction patterns for individual grains in the films demonstrating that preferred orientation growth of the individual crystallites is possible by utilizing the crystallographic relationships between diamond and silicon as discussed above. The selected area electron diffraction patterns show that the diamond film assumes a <110> preferred orientation when grown on a <100> silicon substrate.

The use of preferred orientation diamond films may permit the fabrication of active electronic devices by taking advantage of the expected anisotropic conduction characteristics of oriented diamond films. Anisotropic carrier transport in silicon crystals has been well documented. When parallel arrays of dislocations are introduced into silicon crystals, the conductivity of the crystals is found to be highly anisotropic with respect to the dislocation direction.[17] The individual dislocations can be charged as a result of the presence of unpaired or dangling bonds, resulting in space charge cylinders around the dislocations. The existence of such space charge cylinders around dislocations, and, by extension, around grain boundaries, has the effect of excluding charge carriers from the dislocations. This exclusion would lead to a reduction of the conductivity of the material when the carrier flow is normal to the dislocations, whereas the conductivity parallel to the dislocations should not be affected. In the case of oriented polycrystalline diamond films the fabrication of vertical devices, wherein carrier transport is normal to the direction of growth of the film and hence parallel to the grain boundaries results in a minimization of the influence of the grain boundaries since the cross section presented by the grain boundaries to the flow of charge carriers should be small.

## Device Structures

Diamond metal semiconductor field effect transistors (MESFET) are prime candidates for being the first active devices that may be fabricated in diamond films. Figure 7 depicts, schematically, a basic diamond MESFET structure. Techniques for device isolation, as shown in
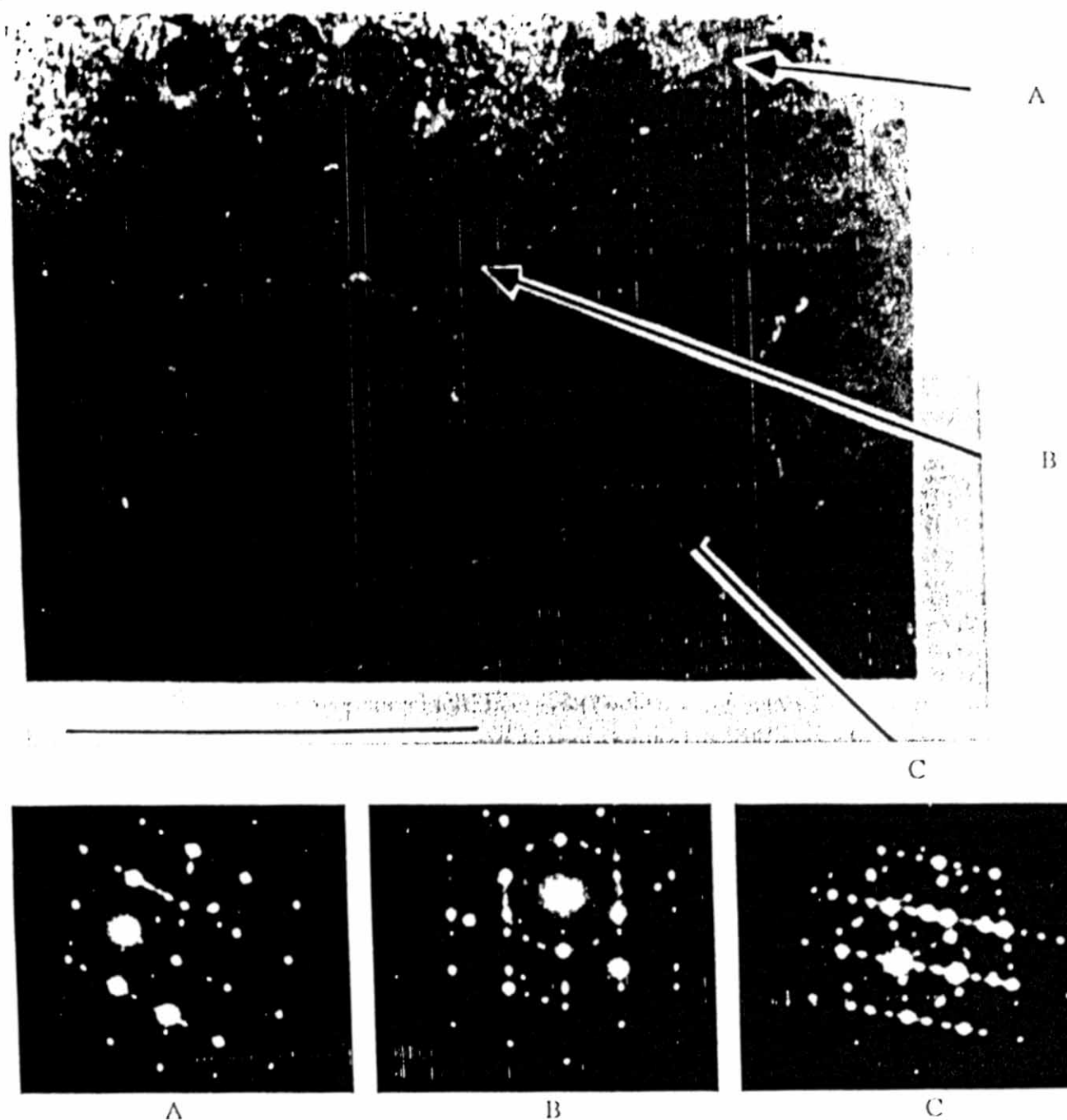
Figure 6. Transmission electron micrograph and associated selected area electron diffraction patterns of a diamond film grown on (100) oriented silicon demonstrating that the individual grains are oriented in a preferred <110> direction .

the bottom sketch of Figure 7, have to be developed by using approaches such as reactive ion etching (using nitrous oxide) to create mesa structures. The other more important aspect of the isolation process is the presence of the undoped diamond layer underneath the channel which both isolates the device and serves as a convenient channel stop.
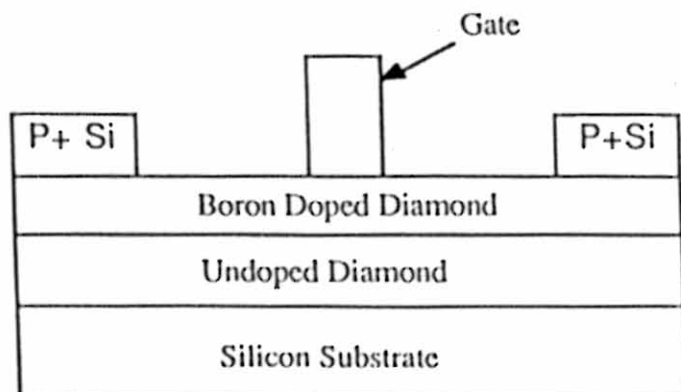
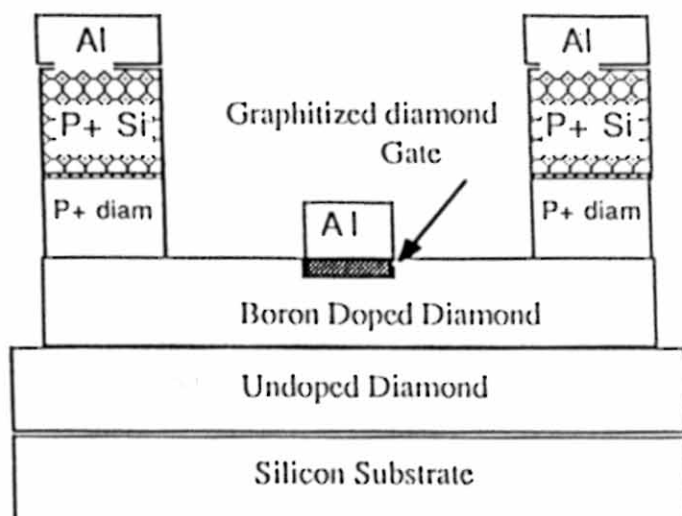Possible gate materials are N+ Si, gold, graphite
and n+ Silicon Carbide



Figure 7. Schematic sketches of Diamond MESFET's.

Assuming that grain boundaries do not interfere with the manufacture of the transistor (i.e. through unwanted rapid grain boundary diffusion) unipolar devices are typically only degraded through a reduction in the mobility and trapped charge in the gate region. This degradation is only on the order of a factor of two due to a reduction in the mobility. The degradation due to traps can be more significant but preliminary published results on Schottky barriers on polycrystalline material show behavior that is at most only slightly affected by traps [13].Trapped charge can, if present in concentrations on the order of the channel charge, prevent MESFET gate modulation altogether or significantly reduce transistor transconductance. The reported results on Au/diamond Schottky barrier capacitance indicates that there are not large trapped charge densities in diamond polycrystalline films. These results indicate that MESFET fabrication should be straightforward. Consequently polycrystalline diamond versions of MESFETs are feasible devices.

# Single Crystal Diamond Films - Status and Prospects

Clearly the realization of the ultimate potential of diamond for active electronic applications requires single crystal diamond films. Homoepitaxial growth of diamond films on single crystal natural diamond substrates has been demonstrated.[18] However the small size of natural or high pressure synthesized diamond crystals and their high cost makes this approach to the growth of single crystal films impractical. Consequently heteroepitaxial approaches are required for this purpose. The requirements associated with the growth of heteroepitaxial diamond can be summarized as follows:

* Lattice matched substrates have to be available for promoting epitaxy.

* The substrates have to be stable and non-reactive with the growing diamond film as well as the plasma under the conditions extant in the reaction chamber at growth temperatures.

* The thermal expansion coefficients of the substrate and the diamond have to be matched in order to prevent excessive interfacial stresses, defect generation and delamination.

* There should be no contamination of the diamond film from impurities in the substrate.

* There should be no catalytic effects of the substrate promoting the formation of $sp^2$ ( graphite ) bonds as opposed to $sp^3$ (diamond ) bonds.

There are no obvious candidates for the ideal substrate for diamond growth. However several avenues of research are available for investigation in order to achieve the desired end result. Small degrees of lattice mismatch between the substrate and the overlying material can be accommodated by the creation of strained layers at the interface as long as the stored energy at the interface is smaller than the reduction in the energy due to dangling bonds when misfit dislocations are created at the interface. Using this phenomenon Si/SiGe heterostructures have been grown by molecular beam epitaxial.[19] Among the common materials available as potential substrates for heteroepitaxy of diamond, copper and nickel have the closest lattice match to diamond with their lattice constants being within 2 % of that of diamond. This is a smaller degree of mismatch than between germanium and silicon ( 4% mismatch ) and successful heteroepitaxy between silicon and germanium has been achieved for the creation of heterostructure single interfaces and strained layer superlattices for altering the band gap and hence the electronic and optical properties of the surface of silicon. Consequently there seems to be ample justification for attempting commensurate heteroepitaxial growth of diamond on single crystal copper, nickel and copper-nickel alloys.

Work to date on attempting heteroepitaxy on single crystal nickel has not resulted in the growth of diamond but of single crystal graphite [20]. The issues that require addressing in this context include the potential for chemical reactions between the nickel and the diamond, the catalytic effect of transition elements in suppressing diamond formation and the relative instability of the nickel surface at the temperatures of diamond deposition typically utilized ( ~ 900°C). Low temperature diamond synthesis whereby the reactions, if any , between the substrates and the diamond films are suppressed and the substrate is stable during the deposition process are likely to be required for the successful growth of heteroepitaxial diamond on lattice matched metal substrates.

## Conclusions

The very attractive electronic properties of diamond warrant the development of processes for the fabrication of devices in this material. Based on the current state of diamond film synthesis technology, these films can find utility in a number of passive electronic applications. The path

towards the effective utilization of diamond films in electronics is likely to proceed along classically developed approaches whereby the sophistication of the device that can be fabricated in diamond would be directly proportional to the quality of the films that can be produced and the ease and the precision with which the films can be doped and contacted with the appropriate contact metals. Well controlled polycrystalline diamond films have utility in a number of passive electronic applications in conjunction with traditional semiconductors like silicon and gallium arsenide. Opportunities also exist for tayloring the structure of polycrystalline films for the fabrication of selected active electronic devices. The realization of the true potential of diamond in active device applications requires the development of heteroepitaxial growth of single crystal diamond films.

## References

1. R.W.Keyes, Proc. IEEE, 225 (1972)
2. E.O.Johnson, RCA Review, 163 (1965)
3. K.Shenai, R.S.Scot and B.J.Baliga, Symposium on Crystalline Silicon Carbide and related materials, Santa Clara, CA., Proceedings in press (1988)
4. N.Fugimori, T.Imai and A.Doi, Vacuum, 36, 1, 99 (1986)
5. K,V.Ravi, L.S.Plano, M.Pinneo, M.Peters and S.Yokota, Paper presented at the First International Conference on the New Diamond Science and Technology, Tokyo, Proceedings in press ( 1988)
6. M.Pinneo and K.V.Ravi, Crystallume, Unpublished.
7. K.V.Ravi and M.Landstrass, First International Symposium on Diamond and Diamond like Films, 175th Electrochemical Society Meeting, Los Angeles, CA. (May 1989)
8. J.Bernholc, A.Antonelle and S.T.Pantelides, SDIO/IST Diamond Technology Initiative Symposium, Arlington, VA. (July 1988)
9. H.Siethoff, W.Schroeter, Philos. Mag. A, 37, 711 (19780)
10. J.M.Fairfield and B.J.Masters, J.Appl.Phys., 38, 3148 (1967)
11. G.D.Watkins, J.R.Troxell and A.P.Chatterje, Proc. Int. Conf. Radiation Effects in Semiconductors, Nice, Ed. J.H.Albany, 16 (1979)
12. G.S,Sandu, W.K.Chu, M.L.Swanson and J.F.Prince, Diamond Optics, Proceedings of the SPIE, San Diego, CA., 37 (1988)
13. G.Sh. Gildenblat, S.A.Grot, C.D.Wronski, M.C.Hicks, A.R.Badzian and R.Messier, IEDM, 626 (1988)
14. J. Narayan, Y.Chen and R.M.Moon, Phys. Rev. Lett., 46, 1491 (1981)
15. J. Narayan and Y.Chen, Phil. Mag. A49, 475 (1984)
16. J.Narayan, A.R.Srivatsa, M.Peters, S.Yokota and K.V.Ravi, Appl. Phys. Lett., 53 (19), 1823 (1988)
17. K.V.Ravi, Imperfections and Impurities in Semiconductor Silicon, J. Wiley and Sons (1981)
18. B.V.Derjaguin, D.V.Fedoseev, V.P.Varnin, E.A. Gorodetskii, A.P. Zakhorov and I.G.Teremetskaya, Sov. Phys., JETP 42, 639 (1975)
19. J.C.Bean, Science, 230, 127 (1985).
20. R.A.Rudder, J.B.Posthill, G.C.Hudson, M.J.Mantini and R.J.Markunus, Diamond Optics, Proceedings of the SPIE, San Diego, CA., 72 (1988)