

Plasma Activated Wafer Bonding of Silicon: *In Situ* and *Ex Situ* Processes

V. Dragoi and P. Lindner

Technology Department, EV Group, 4782 - Sankt Florian, AUSTRIA

Plasma activated wafer bonding generated a high interest in last decade due to the important process temperature reduction. With the main advantage of bringing some applications at industrial degree of feasibility. An example of process which benefits from this new process is silicon fusion bonding: by using plasma activation the bond process temperature and time are reduced at values which make wafer bonding compatible with industrial manufacturing requirements. A newly developed process allowing bonding of two substrates in the plasma activation chamber is foreseen as a very interesting approach for numerous applications, especially in the field of engineered substrates fabrication.

Introduction

The use of standard silicon fusion bonding process for some categories of applications is strongly limited by the high process temperature and long process time. Among these applications can be mentioned bonding of wafers with metal patterns (e.g. Aluminum metallization requires a maximum temperature of 450°C) or bonding of wafers with etched features requiring alignment (e.g. wafers with cavities for Micro-Electro-Mechanical Systems - MEMS). MEMS applications require quite often contacting the wafers under vacuum after precise optical alignment and thermal annealing of the pre-bonded pairs with contact force applied.

The use of a commercially available wafer bonding equipment would be required in order to transfer such applications to medium/high volume manufacturing.

By lowering considerably the process temperature (typically below 450°C) and process time fusion wafer bonding processes can be integrated in manufacturing process flows, similar to already used eutectic wafer bonding or anodic wafer bonding.

Commercially available industrial wafer bonding equipment available from different suppliers has in common some important features: temperatures up to max. 600°C, vacuum capability (in the low and high vacuum range), heating in controlled atmosphere, possibility to apply controlled contact force during annealing.

Surface activation for wafer bonding consists in a wet or a dry chemical treatment of the substrate's surfaces which enables formation of strong chemical bonds subsequently resulting in decrease of thermal annealing temperature and duration.

The use of wet chemical processes is not possible for some applications (especially for patterned wafers containing different coatings and metallizations or containing etched features). For this reason a high interest is focused on dry surface activation methods, consisting in a plasma treatment of the two surfaces prior to bonding (1-4). The choice of the proper plasma type allows the surface chemistry tailoring to obtain the fastest bonding kinetics and highest bond strength at low annealing temperatures.

A newly developed plasma activation process uses a special chamber and is carried at room temperature. The process chamber setup enables the use of different plasmas (different process gases) and makes it applicable for silicon as well as for other materials.

The plasma parameters were optimized in order to avoid producing the most undesired phenomena in wafer bonding: surface etching resulting in increased roughness. The plasma activation process described in this paper was developed to only break the surface chemical bonds in order to allow controlling the bond mechanism.

Two different processes were developed for this setup: *in situ* and *ex situ*.

In the *in situ* process, the two wafers are loaded into the chamber face to face, separated by spacers. The wafers are activated simultaneously by generating a plasma in between. After the plasma treatment the spacers are removed, the two substrates are brought into contact and bond is generated *in situ*. Then the wafers are usually transferred to a bond chamber or a furnace for the low temperature thermal annealing.

The *ex situ* process consists in activation of each wafer individually and then transfer the wafers into a bond chamber for performing the bond. Prior to the bonding step the wafers can be precisely aligned using an optical bond aligner.

This paper presents results obtained for wafer bonding of silicon and silicon dioxide using different plasma activation processes and shows examples of silicon-based applications which benefit from this technology.

Experimental

Plasma activation chamber (figure 1) consists of a low volume chamber with full opening of the chamber lid and a setup of two disc-shaped electrodes. The bottom electrode is used also as wafer chuck.

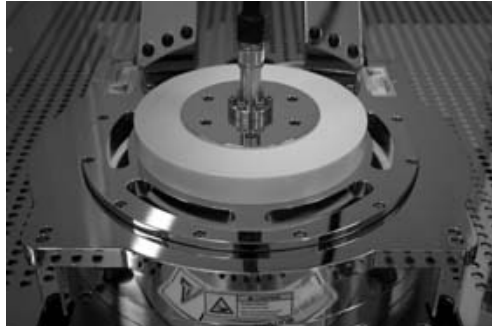


Figure 1. Plasma activation chamber close view.

In the *ex situ* process, one wafer is loaded onto the chuck (bottom electrode) and the wafer surface is exposed to the plasma established between the chuck and the top electrode (figure 2.a). After activation of both wafers these are brought into contact outside the chamber.

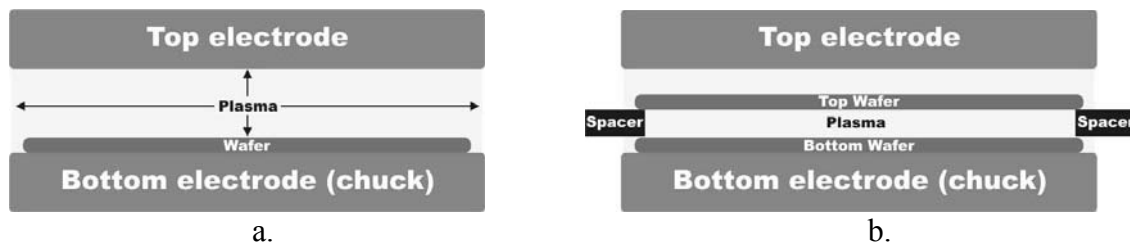


Figure 2. Plasma activated wafer bonding processes: a. *ex situ* process, and b. *in situ* process.

In the *in situ* process a wafer is loaded onto the chuck (bottom electrode), then three thick spacers are pulled at wafer edge and the second wafer is loaded "face-down" on the spacers. The *in situ* process is using a set of mobile parts which are performing the mechanical alignment of the two wafers. When plasma is generated both bonding surfaces are exposed simultaneously to the plasma (figure 2.b).

After activation, spacers are removed and the two wafers are brought into contact without venting the chamber to ambient.

Process flow for the two types of processes is:

1. *Ex situ* plasma activated wafer bonding:

- Wafer cleaning
- Plasma activation
- Optical alignment (optional)
- Pre-bond (wafer contacting) at ambient or in vacuum (in a bond chamber).
- Thermal annealing

2. *In situ* plasma activated wafer bonding:

- Wafer cleaning
- Plasma activation
- Mechanical alignment (*in situ*)
- Establishing the desired atmosphere in the chamber (vacuum, gas at controlled pressure).
- Pre-bond (wafer contacting) at ambient or in vacuum, in bond chamber.
- Thermal annealing (out of plasma activation chamber).

In order to demonstrate plasma activated wafer bonding compatibility with special applications requiring extreme cleanliness conditions particles and metal ions contamination were measured.

Two types of bonds were performed: Si-Si and Si-Si with 500nm thermal oxide. Annealing of the bonded pairs was performed at 200°C and 300°C.

The wafers bonded using the two types of processes were investigated for voids by infrared (IR) transmission. The bond strength was measured using the crack opening method (5).

Results

Ex situ plasma activated wafer bonding

Bond process kinetics

The wafers were activated in Oxygen and Nitrogen plasma and bonded in two different ways: in one approach, the wafers were bonded at ambient immediately after plasma activation and in the second process wafers were first rinsed with water and then bonded at ambient.

High bond strength was observed for annealing 2-3 hours @200°C and 0.5 - 1 hour @ 300°C (detailed results were presented in ref. 4 - figure 3).

The main results of this test were:

1. Plasma activation results in a modification of surface chemistry (two different gases used at same RF parameters and pressures resulted in different results)
2. The use of water rinse between plasma activation and pre-bonding doesn't improve the bond strength but may be beneficial in removing particles which can be trapped on the surfaces during wafer transfer between plasma chamber and bond chamber.

The particular plasma activated bonding process described here is a fully dry process, water rinse may be optionally used just for improving the results in terms of defects.

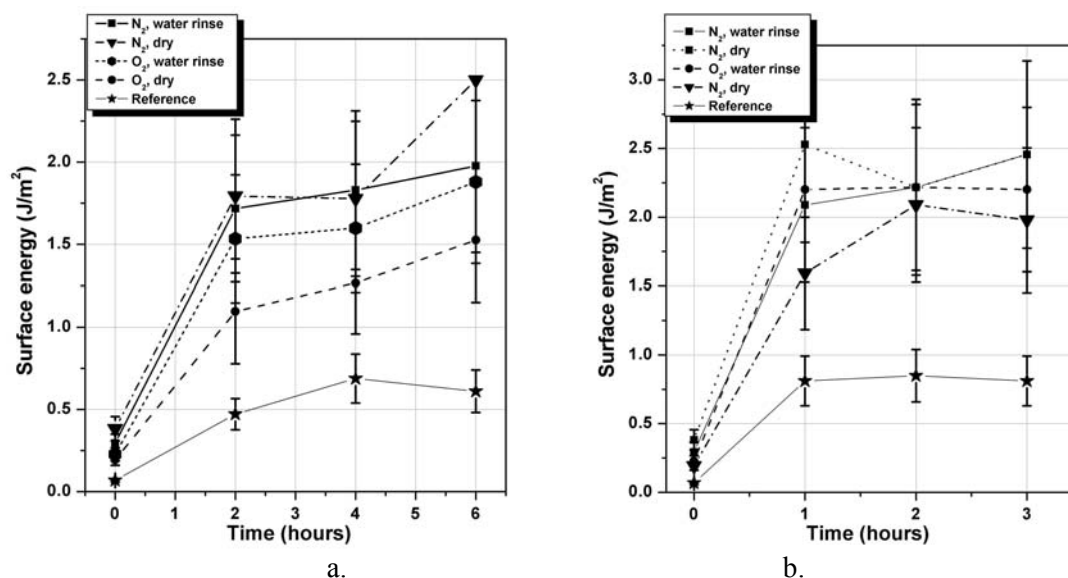


Figure 3. Surface energy vs. annealing time for thermal annealing at 200°C (a), and 300°C (b) for different times.

Temperature pre-bonding

An interesting results was obtained when plasma activated wafers were pre-bonded (contacted) at temperatures higher than room temperature.

Silicon to thermal Silicon oxide samples were bonded using the following procedure:

- Both wafers were activated using same process conditions.
- Wafers were loaded on a bond chuck separated by spacers and mechanically clamped.
- Bond chuck was loaded to a pre-heated chamber and chamber was evacuated for 5 minutes (max vacuum reached $\sim 10^{-3}$ mbar).
- Spacers were removed and wafers were brought in contact starting the bond in the center.
- Wafers were unloaded from the bond chamber and surface energy was measured with crack opening method.
- Bonded pairs were subsequently annealed for 1 and 2 hours at 300°C. After each annealing step surface energy was measured.

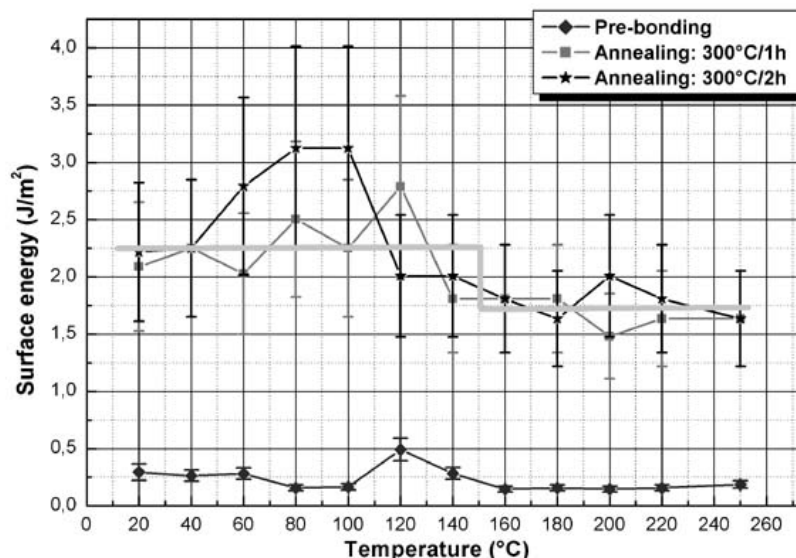


Figure 4. Surface energy vs. pre-bonding temperature.

It can be observed in figure 4 that the values after pre-bonding do not vary much with pre-bonding temperature. After annealing for 1 and 2 hours at 300°C can be observed two regions: samples bonded from room temperature to about 150°C show surface energy values in the range of Silicon bulk fracture strength, while samples pre-bonded between 150°C-250°C show a decrease of the surface energy values to about 1.5 J/m². The gray line in figure 4 illustrates this behavior. It has to be considered that surface energies of ~1.5 J/m² are high enough to allow wafers to survive harsh mechanical post-bonding processes as lapping or grinding.

This result is important mainly for industrial applications in which cooling down of a bond chamber to room temperature in order to start next process would have been totally undesired.

Plasma activated wafer bonding for engineered substrates manufacturing

One important question raised during this new technology development: is the plasma activated wafer bonding compatible with the manufacturing requirements for engineered substrate (SOI, Strained SOI, GeOI)?

It is well known that such applications impose very strict conditions in terms of cleanliness (particles contamination, as well as metal ions contamination). The plasma activated bonding process was characterized from contamination point of view by particles counting and metal ions characterization.

Figure 5 shows particles counts obtained on a lot of 200 wafers (300mm diameter) which were running in a high volume production state of the art equipment used for SOI-type applications. The values obtained are meeting the specification of maximum 10 particles added during process.

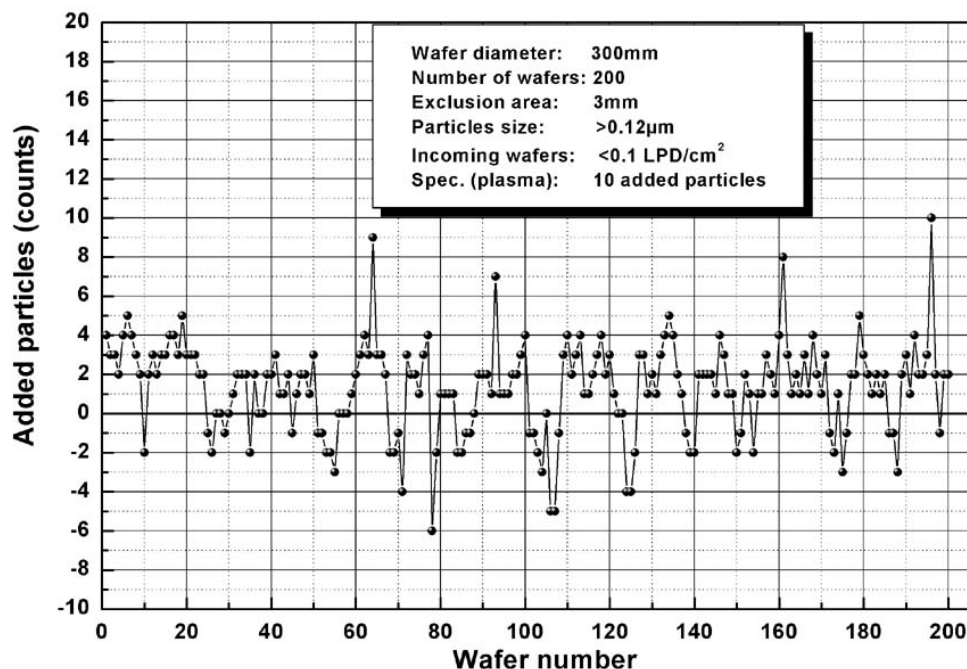


Figure 5. Particles counts measured on a lot of 200 wafers (300mm diameter) running through an EVG® 850LT automated production bonder.

In terms of metal ions contamination induced to the front side, VPD-ICPMS measurements on wafers exposed to plasma in EVG®850LT equipment show values in the range of 10^{10} at/cm², which are compatible with SOI manufacturing (figure 6).

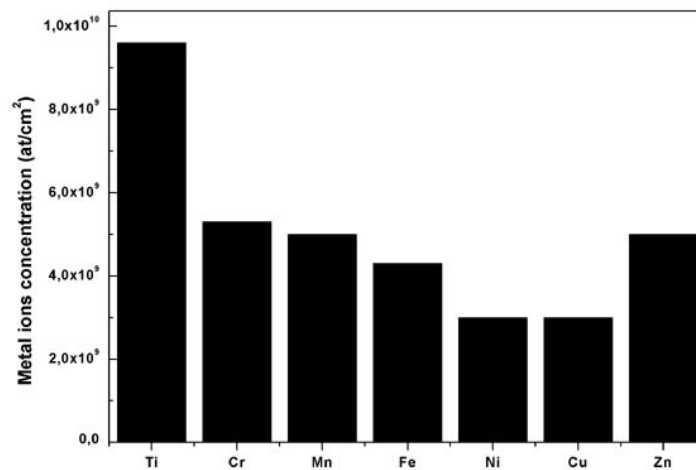


Figure 6. Metal ions concentration measured on reference 300mm diameter wafers running through an EVG®850LT automated production bonder.

In situ plasma activated wafer bonding

Two different plasmas were compared: Oxygen and Nitrogen. Test bonds were performed for Si/Si (prime silicon wafers, (100) orientation) and for Si/SiO₂ (prime Si wafers, (100) orientation, and same type of wafers with 300nm thermal oxide).

In a first test, Si/SiO₂ bonds were performed in order to check the difference between the well established *ex situ* process and the *in situ* process.

For this test, one wafer pair was bonded using a standard plasma activation process with Nitrogen. Two additional pairs were bonded for comparison: one pair with an *in situ* process using same conditions as the *ex situ* process (same gas pressure and RF parameters), and one pair with a process using simultaneous activation of the two wafers as in *in situ* process, manual unloading of the wafers and bonding at ambient, as in *ex situ* process. The results are shown in figure 7.

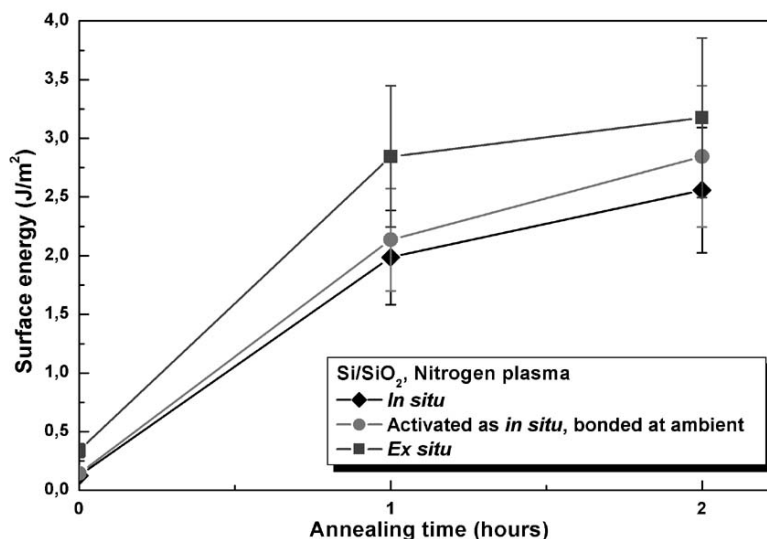


Figure 7. Surface energy vs. annealing time at 300°C for wafers bonded after different plasma activation modes.

It can be observed that the reference pair bonded in *ex situ* process reaches after one hour a surface energy slightly higher than the two pairs activated *in situ*, but all values are in the range of silicon bulk fracture strength.

In a different experiment the same *in situ* process (same plasma activation parameters) was applied for comparing the activation results when using Oxygen or Nitrogen plasmas for bonding Si/Si or Si/SiO₂ wafers pairs (figure 8).

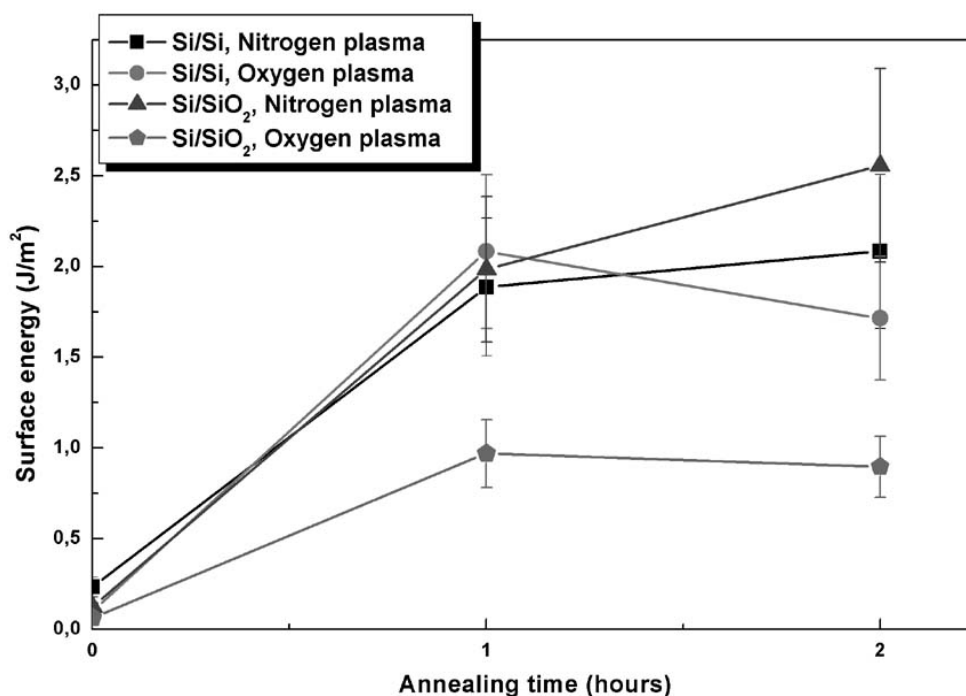


Figure 8. Surface energy vs. annealing time at 300°C for Si/Si and Si/SiO₂ pairs bonded in *in situ* process using Oxygen and Nitrogen plasma.

The surface energy reaches high values for all samples except the Si/SiO₂ bond activated with Oxygen which shows values close to 1J/m².

The surface energy values obtained for nitrogen plasma is high enough to allow bonded pairs survive grinding.

Conclusion

Plasma activation and optically aligned wafer bonding enable new applications in the area of MEMS, as well as in 3D interconnections at wafer level or manufacturing of engineered substrates.

In the MEMS area plasma activated wafer bonding was successfully used for applications based on Si/SiO₂ bonding as well as for Si/Pyrex glass (as an alternative to anodic bonding) and for dissimilar materials integration (Si/GaAs, Si/LiTaO₃, Si/LiNbO₃, GaP/InGaAsP).

An important property of plasma activation process is the compatibility with CMOS technology. CMOS wafers are more and more used for bonding with wafers containing mechanical or optical structures for MEMS/MOEMS devices fabrication. Electrical characterization of the CMOS wafers before and after exposure to plasma showed no

decrease in performance. The low temperature annealing (300°C-400°C) is also compatible with the CMOS technology.

Plasma activated wafer bonding for SOI substrates manufacturing via Hydrogen implantation brings the benefit of enabling the achievement of maximum bond strength at temperatures below the cleaving temperatures, which results in good uniformity of transferred layers.

Introduction of the *in situ* process is very important mainly for manufacturing processes. The important decrease of the process time due to simultaneous activation of the two wafers as well as the lower gas consumption make the *in situ* process an attractive candidate for substrates manufacturing requiring only mechanical alignment.

Another important advantage of the *in situ* process is the decrease of contamination risk: by bonding the wafers immediately after activation there is no handling of the open activated surface which may result in trapping environmental contamination.

A very interesting area to be explored in the future is the use of *in situ* plasma activation process for fabrication of Si/Si oxide-free interfaces. Experiments performed on compound semiconductors showed after exposure to plasma a surface passivation of the semiconductor surface. For few hours no oxide growth could be detected.

Further experiments will consider investigation of oxide-free Si/Si interfaces by electrical characterization as well as by high resolution Transmission Electron Microscopy.

References

1. P. Amirfeiz, S. Bengtsson, M. Bergh, E. Zanghellini and L. Börjesson, *J. Electrochem. Soc.*, **147**, 2693 (2000).
2. M. M. R. Howlader, H. Okada, T. H. Kim, T. Itoh and T. Suga, *J. of Electrochem. Soc.*, **151**, G461 (2004).
3. M. Gabriel, V. Cetin, S. Hansen, M. Reiche, I. Radu and M. Eichler, in *Semiconductor Wafer Bonding VIII: Science, Technology, and Applications*, K. D. Hobart, C. E. Hunt, H. Baumgart, T. Suga, and S. Bengtsson, Editors, PV_2005-02, p. 50, The Electrochemical Society Proceedings Series, Pennington, NJ (2005).
4. V. Dragoi, S. Farrens, P. Lindner, in *Micro- and Nanosystems—Materials and Devices*, C. S. Ozkan, D. A. LaVan, M. McNie, S. Prasad, Editors, vol. 872, p. J7.1.1., Materials Research Society, Warrendale, PA (2005).
5. W. P. Maszara, G. Goetz, A. Caviglia and J. B. McKitterick, *J. of Appl. Phys.*, **64**, p. 4943 (1988).