MICROWAVE INDUCED DIRECT BONDING OF SINGLE CRYSTAL SILICON WAFERS

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Abstract

We have heated polished doped single-crystal silicon wafers in a single mode microwave cavity to temperatures where surface to surface bonding occurred. The absorption of microwaves and heating of the wafers is attributed to the inclusion of n-type or p-type impurities into these substrates. A cylindrical cavity TM_{010} standing wave mode was used to irradiate samples of various geometry's at positions of high magnetic field. This process was conducted in vacuum to exclude plasma effects. This initial study suggests that the inclusion of impurities in single crystal silicon significantly improved its microwave absorption (loss factor) to a point where heating silicon wafers directly can be accomplished in minimal time. Bonding of these substrates, however, occurs only at points of intimate surface to surface contact. The inclusion of a thin metallic layer on the surfaces enhances the bonding process.

INTRODUCTION

The joining of substrates is a subject that is gaining attention due to its importance in various scientific, technological and industrial applications. However, there still remain problems in the standard techniques for bonding various substrates. For example, the bonding of two substrates by conventional means may lead to residual stresses left behind in the bonding process, limited maximum operating temperatures of the bonded materials, or weakened substrates caused by the diffusion of bonding materials into the substrates.

We have used the unique properties of microwaves to demonstrate the bonding of various ceramic substrates such as tungsten carbide to industrial diamond for drilling applications and doped silicon, for use in Micro Electro-Mechanical Systems (MEMS) applications. These substrates were bonded to themselves as well as to each other. Microwave radiation in a cylindrical single mode cavity was used to bond the various substrates. The microwave power absorbed in a material is given by

$$P_{ave.} = \frac{1}{2}\ \omega_0\ \varepsilon_0 \varepsilon'\tan\delta\, E^2$$

where ε_0 and ε' are the free space and material dielectric constant, respectively, and E is the electric field. This mechanism for microwave absorption can lead to very rapid volumetric heating of the material. We attribute the heating of the substrates used in this study to the enhanced susceptibility associated with the n or p-type doping of the silicon.

MEASUREMENTS AND DISCUSSION

All microwave bonding studies were performed in a cylindrical cavity excited in an azimuthally symmetric TM_{010} mode at 2.45 GHz. Figure 1 shows the experimental arrangement. The experiments were performed in a high vacuum (~25 μTorr) to avoid the creation of plasma. The two substrates were positioned inside of a microwave transparent quartz tube such that the wafers were oriented inside the cavity parallel to the magnetic field at its highest intensity. The initial microwave study demonstrated bonding of two substrates without any metallization to enhance the bonding. While these experiments were successful, the bonds between the substrates were not uniform. In the next stage of this study, we

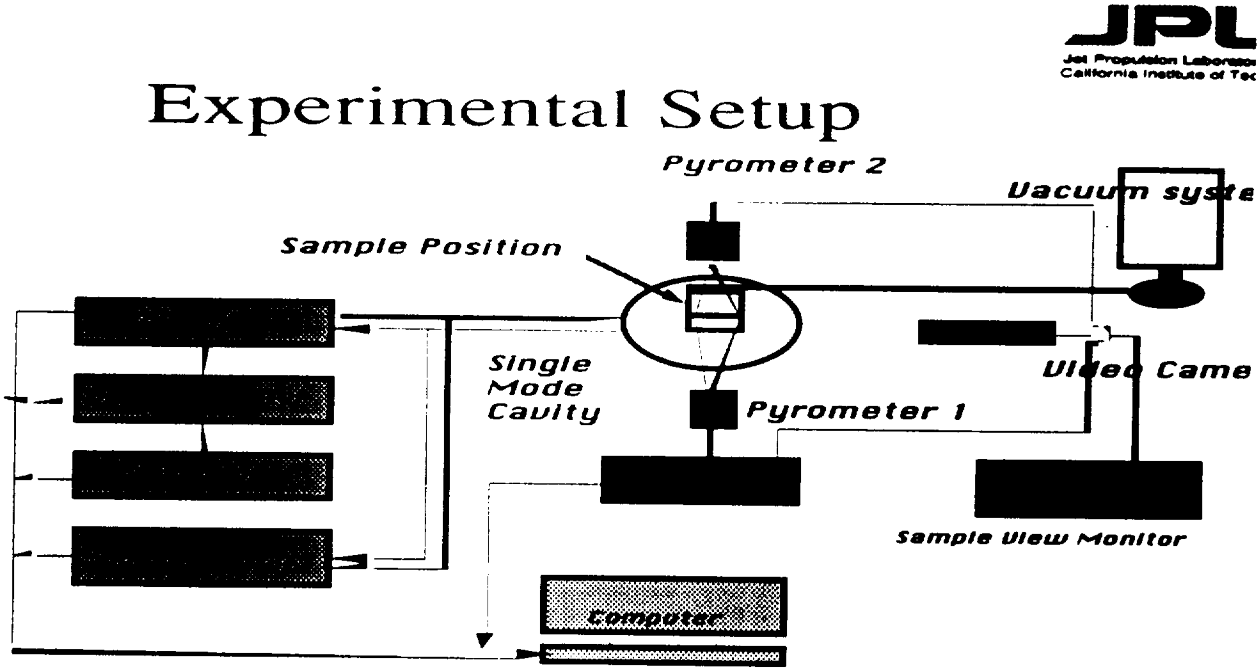

Figure 1. The experimental set up shows the components for the experiment

investigated the ability of microwaves to selectively heat metal films deposited on the substrates to form stronger bonds. This demonstration study used gold on silicon substrates (Au/Si). The test pieces were fabricated using standard lithographic techniques as fully described in an earlier work[1]. Each bonded device consisted of one 5 mm x 5 mm x 500 μm test piece and one cover piece. Figure 2 shows some test pieces with the 3 mm x 3 mm x 100 μm deep etch pit surrounded by a 2 mm wide by 0.1 μm thick plateau of Au. The cover piece consisted of a 10 μm Au silicon wafer with a Cr diffusion barrier in between the Au and the Si. This Cr diffusion barrier prevented the formation of an Au-Si eutectic with weaker mechanical properties. The cover piece was placed underneath the upper substrate with the Au perimeter.

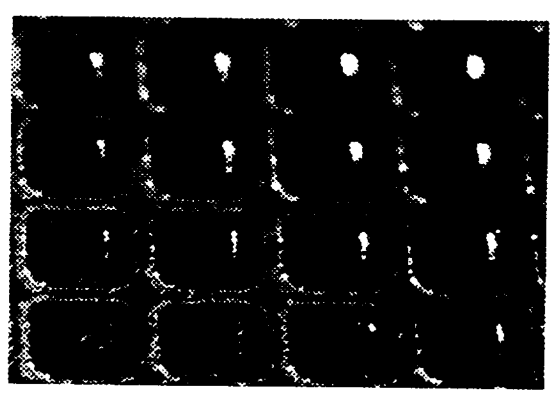

Figure 2 Au Perimeter On Si Wafers

With this configuration microwave energy was deposited in the metallic portion of the substrates since the loss tangent is much higher in metals than any other materials. Most of the energy was selectively deposited in the thin metal films. This concentration of the energy locally melted the metal and bonds form rather quickly with minimal heating of the substrate. The short bonding process-time allows for minimal Si or Au diffusion. Mechanical stresses were minimized since no pressure was applied during the bonding. Various power-time profiles were applied to achieve the bonding. Some of these profiles were performed at high-power (~300 Watts) for short times (~2-3 second duration). Other profiles lasted for ~30 seconds at ~100 Watts. Successful bonding was achieved for all of the profiles tested. We are working on controlled experiments to indicate the profile that achieved the optimum bonding.

Substrates with a Au rim perimeter were bonded to a Au coated ultra thin wafer forming a hermetically sealed micro-cavity. The hermeticity of the bonded pieces was initially apparent after microwave heating by the inward bulging of the thin cover piece due the pressure difference between the inside and outside of the enclosure (see Figure 3). The strength of the bond is shown in Figure 4, where the thin membrane was intentionally broken by applying increasing levels of mechanical stress. Even when failure occurred, the bonded borders remained intact.

Figure 2. Microwave bonded test pieces showing the dipping in the center due to the fact the hermetic sealing occurred under vacuum.

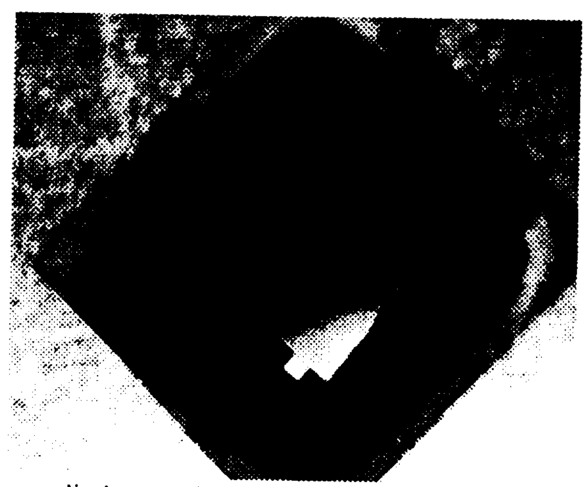

Figure 3. When the applied stress breaks the membrane, the perimeter is still bonded.

Qualitative mechanical testing of the bonded wafers indicated the bond strengths depended heavily on surface morphology[2] and cleanliness. The mechanism for this bond formation is presently not well understood. We speculate that impurity bonds (e.g. Si-O-Si) or direct silicon to silicon bonds are formed and are responsible for the formation of the bonded structure.

CONCLUSION

Heating of n-doped (or p-doped) silicon wafers to very high temperatures was achieved in a single mode microwave cavity. Bonding of Si to Si substrates depended on surface topology. A significant improvement in wafer bonding was achieved by the introduction of a very thin (< 0.2 μm) metallic layer between the substrates. This improvement was demonstrated using microwave radiation to bond a gold coated thin silicon membrane to a thick similarly coated Au/Si substrate. In this technique the metal films are preferentially heated to melting. The bonding formed a hermetically sealed enclosure. The concentration of heat in the metal joined the surfaces of the two substrates without applying any pressure. Undesirable diffusion of the Au or Si was minimized due to the speed of this microwave bonding technique.

A new bonding study in now underway. This study will evaluate the microwave bonding of more complicated metal film patterns using masking techniques. This masking technique has the capability to shield electronic components from microwave energy. If successful, this microwave technique could have a wide range of wafer bonding applications in the production of electronic devices.

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REFERENCES

[1] Nasser K. Budraa, et. al. 'Low Temperature and Low Pressure *Twelfth IEEE International Conference on Micro Electro Mechanical Systems*, IEEE Catalog Number: 99CH36291C, ISBN:0-7803-5194-0, page 490-492.

[2] C. Gui, M. ELWENSPOEK, N. TAS, AND J.G.E. GARDENIERS, 'The Surface Adhesion Parameter: A Measure For Wafer Bondability ', *Twelfth IEEE International Conference on Micro Electro Mechanical Systems*, IEEE Catalog Number: 99CH36291C, ISBN:0-7803-5194-0, pp. 290-295.