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Chip-Level Vacuum Packaging of Micromachines Using NanoGetters

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Abstract- **A new approach to vacuum packaging of micromachined resonant, tunneling, and display devices is covered in this paper. A multi-layer, thin-film getter, called a NanoGetter, which is particle free and does not increase the chip size of the microsystem has been developed and integrated into conventional wafer-to-wafer bonding processes. Hermetic electrical feedthroughs are also provided as part of this total-solution technology. Experimental data taken with silicon resonators is presented in which Q values in excess of 21,000 have been obtained. Applications for this technology include gyroscopes, accelerometers, displays, flow sensors, density meters, IR sensors, microvacuum tubes, RF-MEMS and pressure sensors.**

***Index Terms*: getter, vacuum packaging, resonator, chip-scale package, MEMS, hermetic electrical lead transfer**

I. INTRODUCTION

Chip-level vacuum packaging through wafer-to-wafer bonding has been undertaken for fragile micromachined devices such as accelerometers, gyroscopes [1-3]. Many MicroElectroMechanical System (MEMS) devices, such as resonators and tunneling sensors, rely on vacuum packaging for improved performance [4-10]. Fig. 1 shows an example of density meter chip packaged in this manner [8]. Devices that must operate under vacuum start development in a laboratory bell jar [11,12]. If functionality is demonstrated, packaging often progresses to a solder or weld sealed ceramic or metal package [13]. If the microsystem has high-volume applications then chip-level vacuum packaging, preferably performed at the wafer level is developed. Traditional vacuum wafer bonding methods include anodic, glass frit, eutectic, solder, reactive and fusion bonding [4,14-17]. One problem encountered with existing wafer-to-wafer vacuum bonding is relatively high cavity pressures that change with time and temperature. Anodic bonding is known to generate oxygen and result in cavity pressures of 100 to 400 Torr (13-53 KPa) [18]. Solder bonding produces cavity pressures between 2 Torr (266 Pa) due to surface desorption of gases. Baking wafers prior to solder reflow does reduce the amount of adsorbed water but only lowers the microcavity pressure from 2 Torr to 1 Torr (133 Pa) [17]. While the pressure of the vacuum wafer bonding system

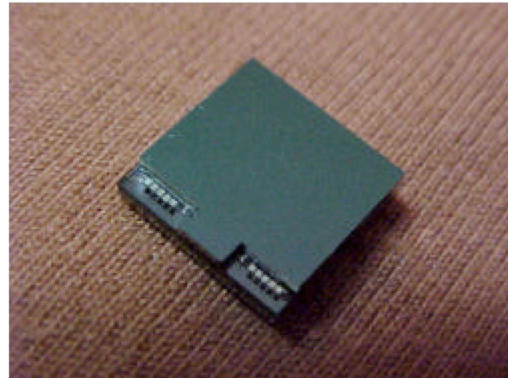

Fig. 1. Chip-scale MEMS package.

can get down to the microTorr level, ultimately surface desorption after sealing limits the cavity pressure.

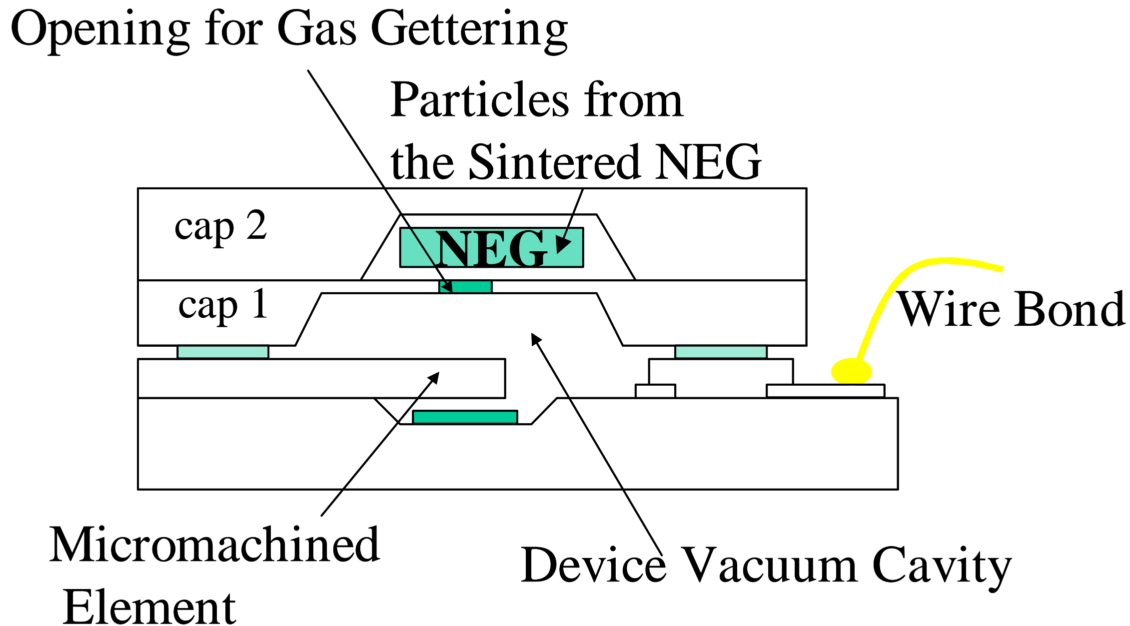

Fig. 2. A cross-sectional illustration of one of the previous methods of integrating NEGs into a vacuum microsystem.

While baking of surfaces can succeed in desorbing gases from surfaces [17,19,20], temperature and time limits the effectiveness of this method in obtaining ultra low cavity pressures in microsystems. Shallow CMOS junctions, thin film alloying and cantilever warpage limit prebonding bake temperatures. To overcome the surface desorption limit found with wafer bonding, getters have been employed. Metallic getters have been used for decades dating back to vacuum tubes to obtain lower pressures in hermetic packages [21]. Pure metals and alloys of Ba, Al, Ti, Zr, V, Fe and other reactive metals are used in cathode ray tubes, flat panel displays, particle accelerators, semiconductor processing equipment and other vacuum equipment to lower the pressure [22-25]. These metals trap various gases through oxide and hydride formation and by simple surface adsorption. Capture of oxygen, nitrogen and hydrocarbons requires elevated temperatures (200 to 550?C), while trapping of hydrogen by the metals occurs at room temperature. Esashi and others [18, 26,27] first applied getters to MEMS devices in the mid 1990's. In these early studies, NonEvaporable Getters (NEGs) either in tablet or

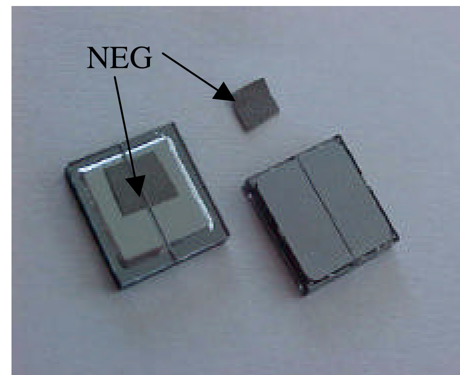

Fig. 3. A silicon –on-glass pressure sensor, vacuum sealed with an NEG.

strip form were placed in an extra micromachined cavity or adjacent to the chip in a ceramic package. To maximize surface area, the NEG is often fabricated using powder metallurgy techniques in which the sintering of the metal particles is just initiated, leaving gaps between metal beads. A high temperature activation step in vacuum or a hydrogen containing reducing ambient is required to remove the surface oxide layer that forms on the metal particles during the sintering process. This activation step is accomplished by either through annealing the whole package or by Joule heating of the NEG strip. One problem encountered with sintered getters is particle generation. When NEG metal strips are employed, they are typically cut into small segment and hand placed into a microcavity prior to wafer bonding. The strips often bend during cutting, requiring additional manual handling to straighten the pieces. Particles are generated during handling and the cutting process. The 2 to 3 micron diameter metal particles can cause electrical shorts, impede motion and shift resonant frequencies. A frequency shift occurs due to a mass change in the resonator caused by the attached particle. Fig. 2 shows an example of one way that an NEG can be integrated into a microsystem. In this illustration the NEG is located in a second cavity above the micromachine. An opening in the silicon diaphragm separating the NEG from the resonator provides access between the NEG and resonator chamber. Particles that shed from the sintered NEG can also migrate through this opening to the resonating or tunneling element cavity. Fig. 3 shows a photomicrograph of a pressure sensor in which a glass cavity underneath a pressure sensor contains the sintered getter strip [28]. For side-by-side cavity designs the die size area is essentially doubled, while for a vertical integration, such as is

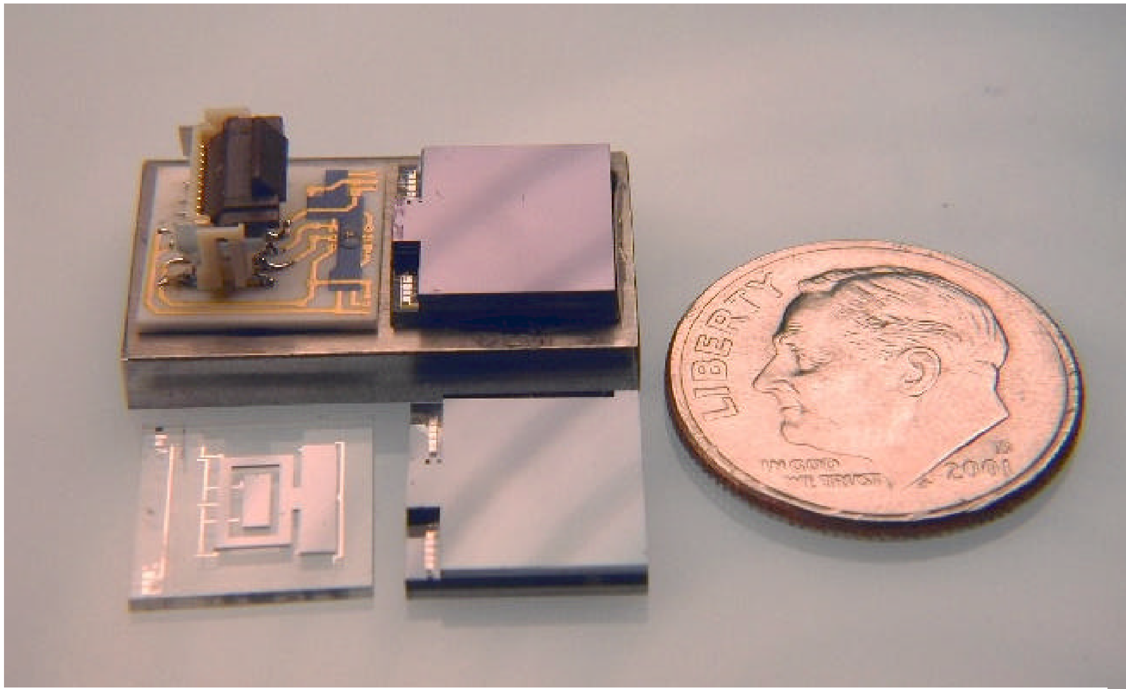

Fig. 4. The uncapped resonator, bottom left and capped chip along with the fluidic header the MEMS chip is attached to, top left.

illustrated in Fig. 2, the chip thickness is increased. The size penalty and need for pick and place NEG loading also prevents the NEG method from finding use in high-volume

MEMS products. This paper will describe a new method of chip-level vacuum packaging MEMS devices with an improved, particle-free getter that does not increase the die size of the chip.

II. EXPERIMENTAL

MEMS Processing

The micromachined resonators used in this study are solid or hollow silicon resonators, shown at the bottom left of Fig. 4 [8]. The hollow resonators are used in producing fluidic density sensors or Coriolis mass flow sensors [8,12]. The resonators are formed by anodically bonding a patterned silicon wafer to a metallized, etched glass wafer. Metal electrodes are formed on the glass wafers to act as drive and sense elements. A final wafer bonding process, including hermetic electrical lead transfer, is performed next to seal the resonator in a vacuum.

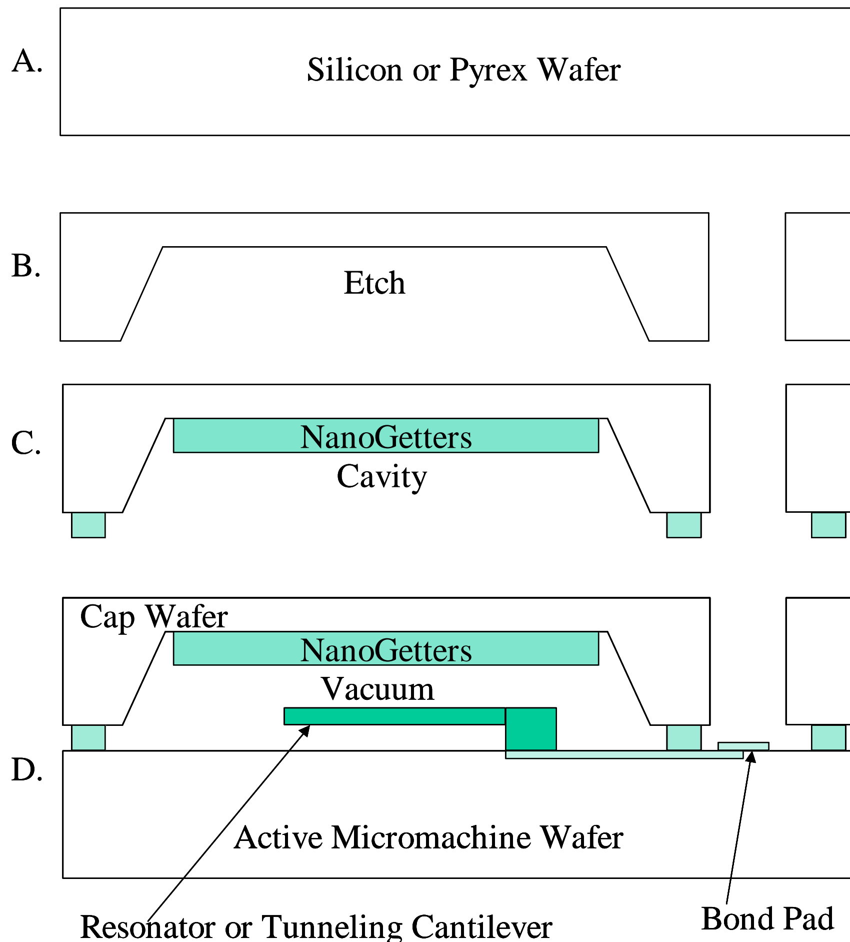

Fig. 5. The process flow for wafer bonding, including the addition of the thin film getter used to form the chip-level vacuum package.

Vacuum Packaging

Initially an NEG was integrated into the MEMS process flow and a device as shown in Fig. 2 was produced. Due to the particle and handling problems associated with NEGs that were mentioned in the introduction section, a new vacuum packaging method and getter were developed. The wafer bond packaging process for this new approach is illustrated in Fig. 5. A capping wafer, generally either silicon or glass is patterned and etched to form both a cavity that will enclose the active micromachine and open up access to the electrical bond pads. Next the Nanogetter and the sealing material are placed on the cap wafer and activated. The NanoGetter is comprised of a proprietary, patent pending, multi-layer structure and as the name implies the thickness of the thin film layers are in the nanometer - 5nm to 500nm- range. Since thin film deposition techniques are employed in a cleanroom environment, the NanoGetter is virtually particle free compared to conventional NEGs formed using powder metallurgy. A surface texture comparison between the NEG and a NanoGetter at 200X, is shown in Fig. 6. The thin film deposition method also enhances the ability to easily integrate the NanoGetter into a typical MEMS process flow at the wafer level. For a conventionally wafer bonded device the process shown in Fig. 5 would look the same minus the NanoGetter

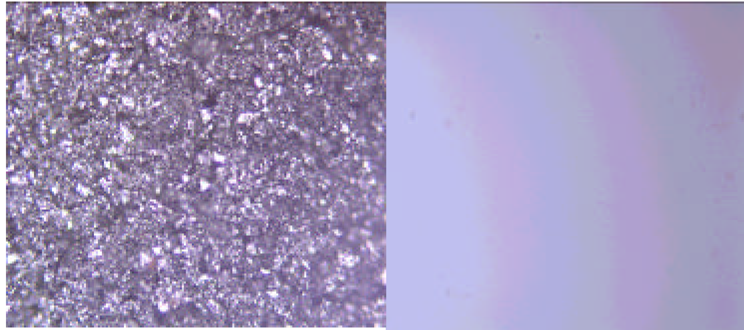

Fig. 6. A pair of 200X optical photomicrographs of an NEG surface (left) and a thin film NanoGetter surface (right).

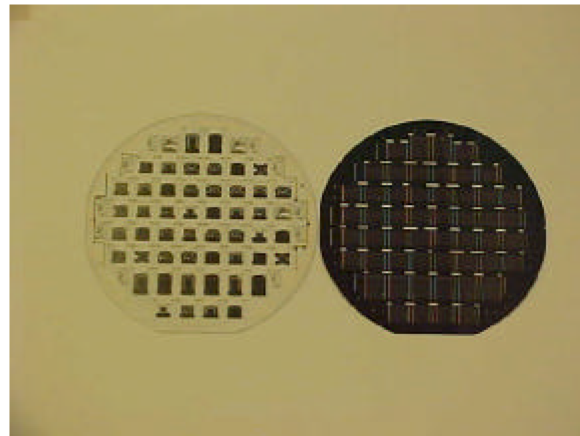

Fig. 7. The active MEMS resonator wafer, left, and the cap wafer, right, prior to wafer bonding.

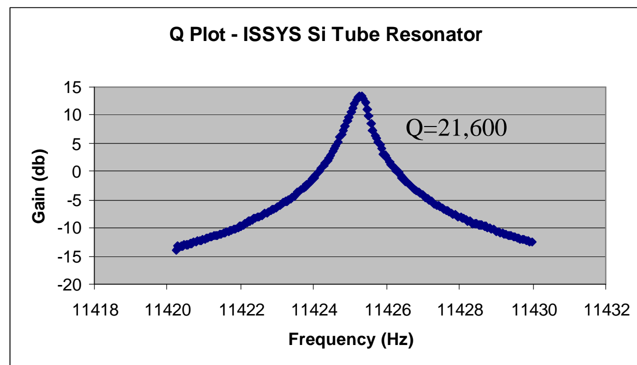

Fig. 8. Q-plot for a silicon resonator vacuum packaging using the NanoGetter.

deposition step. Figure 7 shows the cap and active MEMS wafers prior to bonding. In the majority of vacuum packaged microsystems the capping wafer is part of a passive enclosure. Adding the NanoGetter does not impact the chip size. Vacuum wafer-to-wafer bonding is performed next in this process as illustrated at the bottom of Fig. 5. A vacuum wafer bonding system, an Electronic Visions 501S, was employed in this study. For the devices under discussion in this paper the top cap was etched silicon, bonded with glass frit to the bottom Pyrex wafer which had either a solid or hollow tube silicon resonators on them.

Electrical Testing Procedures

An HP 4194A Phase-Gain Analyzer was employed to take test results on vacuum quality, resonant frequency, and gain. The Q was calculated using the frequency bandwidth where the gain for each of both frequencies is 3 db down from the peak gain. Uncapped resonators were tested in a vacuum chamber. A Varian V-250 turbo pump was used to pull a vacuum in this system.

III. RESULTS AND DISCUSION

Through wafer-to-wafer bonding and the use of NanoGetters a vacuum level under 850 micro-Torr, resulting in Q values greater than 21,000 for silicon resonators can be obtained. Q values have ranged from 5000 to over 21,000 over a period of 8 months on many separate wafer lots. Fig. 8 shows a gain versus frequency plot for a U-shaped single crystal silicon tube that vibrates in the vertical direction. To determine what pressure the high Q values corresponded to a resonator was decapped and tested in a vacuum chamber. Fig. 9 shows how the Q varied with pressure for the relatively wide, U-shaped resonator. With a turbo pump, the chamber pressure could only be pumped down to 790 microTorr (0.10Pa), which resulted in a Q of 10,350 for the die used to generate the data in Fig. 9. Plotting 1/Q versus pressure results in a linear relationship and an intercept or maximum Q value of 13,065 for this particular device. Only a slight increase in Q would be expected at pressures below 790 microTorr. Without the NanoGetter a cavity pressure of 1.4 Torr is obtained with glass frit sealing due to squeeze-film damping caused by desorbed, trapped gas. A Q value of 40 is obtained for this wide resonator

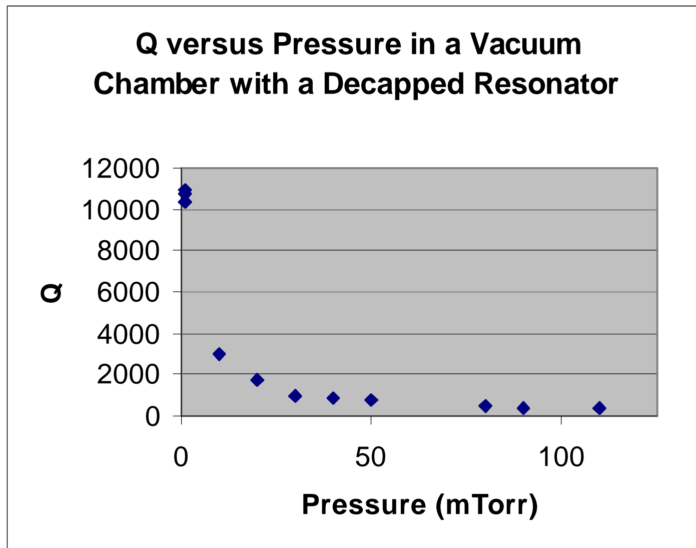

Fig. 9. Q versus pressure plot using a vacuum chamber.

when vacuum packaged without a getter. The microcavity pressure has been reduced by more than 3 orders of magnitude through the use of the getter. The key to obtaining high Q values in a chip-scale package is the NanoGetter placed in the cavity of the cap wafer as illustrated in Fig. 5. This getter technology has been applied to chip-scale vacuum packaging of commercially available microfluidic density and chemical concentration meters [8] and micromachined Coriolis mass flow sensors of different flow rate ranges and hence resonator sizes [12].

Glass frit and anodic sealing have been used for many years in automotive and medical MEMS applications and so have had to pass extensive reliability testing [4,29]. Glass frit sealing has been coupled with silicon, Pyrex, CMOS integrated MEMS, capacitive and piezoresistive devices [29]. To confirm the long-term hermeticity of the glass seal, 46 parts were subjected to a prolonged 95?C bake. No loss of vacuum was noted in any of the 46 parts for over one year. Resonators have shown no significant change in Q after 750 hours at 95?C. Other long-term studies of chip-packaged resonators (gyroscopes) without getters have shown a gradual degradation in vacuum quality due to desorption after several hundred hours at 85 to 100?C [30]. For commercially available modules employing NanoGetter technology [8] thermal shock from 0 to 125?C, biased humidity testing at 85?C, 90%RH, vibration and system level drop testing have also been performed. No loss of hermeticity or getter related particle generation has been observed.

Since several vacuum sealing technologies exist and each can result in different residual gases of varying pressures, it would be ideal to have a flexible getter approach. Anodic bonding is known to generate relatively large amounts of oxygen as the sodium in the glass is ionized under bias at high temperature [18]. A thicker getter layer, than needed for other bonding methods, is required to chemisorb the high concentration of oxygen produced by the anodic bond process. Glass frit and solder can outgas water or carbon dioxide, requiring a compound that absorbs hydrogen and carbon. Reactive sealing using an oxide, nitride or polysilicon deposition process [32] would require the ability to getter hydrogen left behind after chemical vapor deposition processing, therefore different Nanogetters have been developed for these applications. Care must be taken in MEMS design with reactive encapsulation to insure that the getter surface is not coated during sealing. This NanoGetter technology offers the flexibility to customize the NanoGetter layers used and the thickness employed which is of great advantage in changing the getter for different MEMS encapsulation processes. The deposition of NanoGetters is not limited to MEMS chips. Both MEMS die and conventional metal and ceramic vacuum packages, see Figure 10, can incorporate a patterned NanoGetter on either the lid or other

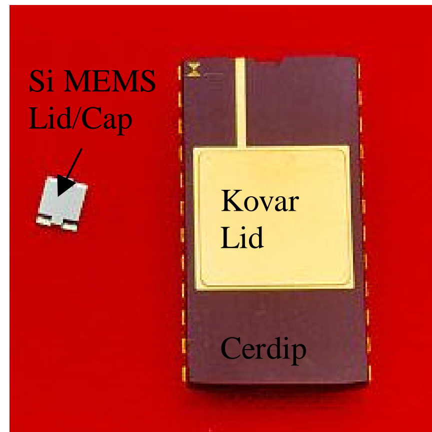

Fig. 10. Chip-level and side-brazed ceramic package using NanoGetters deposited on the underside of the lid.

surfaces.

This new approach to obtaining ultrahigh vacuum in a microcavity has the potential to see widespread use in the field of MEMS. The performance of so many resonating devices can be improved through higher Q and gain. High-volume devices like motion and pressure sensors as well as RF-MEMS chips can benefit from this technology. In addition to improved device performance, the long-term reliability of both resonators, tunneling devices and pressure sensors can be improved with lower cavity pressures. In automotive applications, sensors and actuators are expected to maintain tight specifications for 5 to 10 years operating at temperatures between –40?C and 85 to 150?C. Long-term Q and sensitivity degradations, which were partially reversible and traceable to adsorbed gases have been observed with MEMS gyroscopes [30]. Tunneling tip coating can lead to work function and output drift and has been improved with vacuum packaging [10]. Millions of absolute pressure sensors are produced each year for a variety of applications and they are also prone to temperature hysteresis due to packaging stress and potentially from reversible microcavity gas desorption [29]. Fig. 11 shows how the NanoGetter could be applied to improve the long-term temperature performance of pressure sensors. This technology has been developed at an organization that offers MEMS wafer fabrication and design services [31]. NanoGetters are available for widespread use by the microsystem academic and industrial community.

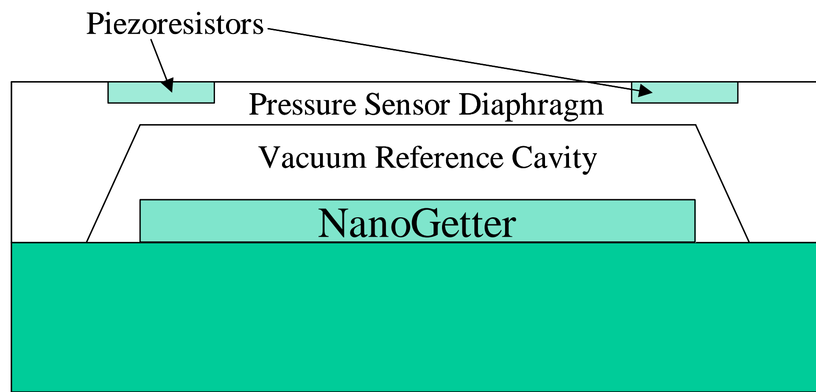

Fig. 11. The application of NanoGetters to a piezoresistive pressure sensor.

IV. CONCLUSIONS

A new vacuum packaging method, including hermetic electrical lead transfer, for micromachined resonant, display and tunneling devices is covered in this paper. A multi-layer, thin-film getter, called a NanoGetter, which is particle free and does not increase the chip size of the microsystem has been developed and integrated into conventional wafer-to-wafer bonding processes. Experimental data taken with silicon resonators is presented in which Q values in excess of 21,000 have been obtained, indicating vacuum levels below 850 micro-torr. This new technology can be applied to packaging gyroscopes, accelerometers, displays, flow sensors, density meters, IR sensors, microvacuum tubes, RF-MEMS and pressure sensors.

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