Application of YAG Pulsed Laser Micro-Welding in MEMS Packaging

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ABSTRACT

This paper reports a new packaging method for a wide range of MEMS for application on both the wafer and device scale. Titanium is used as the packaging material in this work and both silicon and titanium MEMS devices are integrated on to a titanium substrate. A Nd:YAG pulsed laser is used to micro-weld the titanium cap to the substrate. A three-dimensional time dependent model of heat flow during laser beam welding is presented. The heat transfer and parametric design capabilities of COMSOL were employed for this purpose. Model calculations were compared and calibrated with experimental results of pulsed laser welds. The proposed technique is applied to package an AFM cantilever tip. The experimental measurements show that the resonance frequency and quality factor of the device stay the same before and after packaging and the applied technique has no effect on the device.

Keywords: mems, packaging, pulsed laser, titanium, micro-welding.

1 INTRODUCTION

Packaging provides structural and environmental protection for MEMS devices to enhance their reliability but poses a critical challenge for the commercialization of MEMS products. Techniques that are compatible with wafer level fabrication, low temperature processing, vacuum and hermetic encapsulation, and standard MEMS post-fabrication approaches are needed in many applications.

Although Au-Au and Si-Au eutectic bonding [1] and anodic bonding [2] have been widely used in MEMS packaging, these global heating packaging approaches still have several drawbacks. They are not reproducible, have surface and intermediate film dependency, and require various high temperature steps for bonding. As such, no temperature sensitive material survives through the bonding process.

In this work, we use titanium as the packaging material with a pulsed laser to locally heat and micro-weld a titanium cap to the substrate. The proposed method addresses the drawbacks of eutectic and anodic bonding approaches. Titanium has been studied as a new material to produce MEMS [3]. This paper introduces titanium as an advantageous MEMS packaging material due to its excellent biocompatibility, corrosion resistance, high strength-to-weight ratio, weldability [4] and potential *in vivo* applications in biotechnology [5].

Laser welding in this paper refers to the low repetition rate regime in which significant resolidification of workpiece occurs between laser pulses. Pulsed laser welding offers the advantage of very low heat input to the weld, resulting in low distortion and the ability to weld heat sensitive components.

2 PHYSICS OF LASER WELDING

There have been several numerical and analytical models that have sought to elucidate the physical mechanisms involved in the continuous-wave laser welding process [6-8], but only a few models of pulsed laser welding exist [9]. In order to construct an adequate model of heat flow in pulsed laser welding, it is necessary to understand the physics of the laser welding process.

When a laser beam is irradiated onto the surface of a material, the absorbed energy causes heating, melting and evaporation of the material depending on the absorbed laser power intensity [10]. Laser welding is performed by moving the focused beam over the surface of the workpiece along the desired contour that separates the two pieces to be joined. If the laser beam intensity is sufficiently high and the scanning speed is not too fast, evaporation throughout the full depth of the workpiece can be obtained and the so called keyhole is formed, see Figure 1.

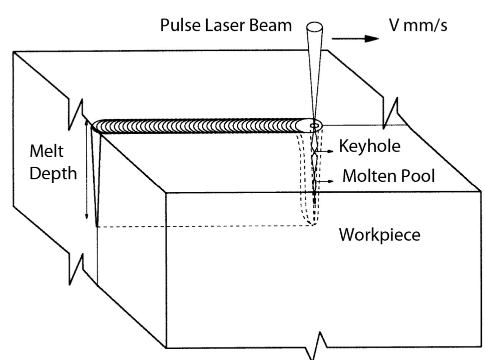

Figure 1: Schematic of keyhole, melt depth and molten pool in pulsed laser welding.

This keyhole absorbs a considerable amount of the laser beam power. Thus, the keyhole plays an important role in transferring and distributing the laser energy deep into the material and provokes melt depth [11]. The thickness h of a laser-induced melting layer is an important parameter in pulsed laser interaction with the material surface. It is a key factor for quantifying hermiticity of laser welding. Previous studies on the melt depth of pulsed laser [12] showed that the thickness h is a function of many parameters

$$h \propto \left(I, \tau, \alpha, A, \chi, C, \varphi, q, T_m, T_b, T_i, D\right) \quad (1)$$

where I is the laser intensity, τ is the pulse duration, α is the absorption coefficient, A is the surface absorptivity, χ is the thermal diffusivity, C is the specific heat, φ is the angle of incidence, q is the latent heat of melting, T_m and T_b are the melting and boiling points, T_i is the initial temperature, and D is the laser focal spot size.

3 APPROACH AND MODELING

The approach of this paper is to investigate the correlation between the melt depth and the generated heat in pulsed laser welding and to optimize h based on minimizing the heat.

Optimization of the melt depth requires knowledge of the behavior of h over a wide range of the parameters. As a first step, vaporization effects are not considered in our simulations. We present a 3D time and spatial heat flow model in COMSOL to determine the melt depth and generated heat for various laser parameters such as intensity, pulse duration, pulse frequency, laser focal spot size, and welding speed. The spatial and temporal temperature distribution $T(x,y,z,t)$ satisfies Equation (2) for three-dimensional heat conduction.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + I = \rho c\left(\frac{\partial T}{\partial t}\right) \quad (2)$$

where k_x, k_y and k_z are thermal conductivity in x, y and z directions, I is the laser power, and ρ is the density of the material.

We modeled the pulsed laser as a 3D dynamic Gaussian heat source as shown by Equation (3)

$$I = (1-R)\frac{4I_0}{\pi D^2}\exp\left[-\left(\frac{(x-x_0)^2}{2r^2} + \frac{(y-y_0)^2}{2r^2}\right)\right] \quad (3)$$

where R is the reflectivity of the material the laser is radiated on, I_0 is laser intensity, D is the laser focal spot diameter, x_0 and y_0 are the center of the laser spot which can be express by Equation(4)

$$x_0 = vt \text{ or } y_0 = vt \quad (4)$$

where v is the welding speed and t is the pulse laser period.

As shown in Figure 2 by combining Equation (3) and (4), the Gaussian heat source can be moved along the workpiece with the laser beam scanning speed.

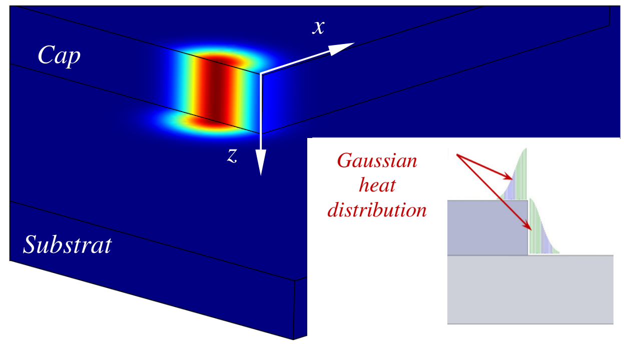

Figure 2: The pulsed laser was modeled as a 3D dynamic Gaussian heat source. The Gaussian heat source was distributed evenly on the cap and substrate.

3.1 Simulation

In our model, a MEMS device was mounted on a 10 mm titanium substrate and an 8 mm titanium cap was used to weld it to the substrate, see Figure 2. The cap and substrate were taken from a 350 µm titanium wafer. The laser system used in this model to generate heat was assumed to be a pulsed laser with a rectangle pulse shape. Therefore, the Gaussian heat source in our simulation was turned on and off with the frequency of the pulse laser. Various laser parameters such as laser intensity, pulse energy and pulse duration were investigated to determine the correlation between the parameters and the melt depth in laser welding. Previous studies on titanium pulsed laser welding showed a linear relationship between the melt depth and laser intensity [13]. The heat generated by increasing laser intensity can be harmful for the mounted MEMS device. Therefore we focused on the other laser parameters in our simulation such as pulse energy, pulse duration and laser focal spot size.

We performed several experiments and used the experimental results to calibrate our model. The experimental results showed that for a pulsed laser with a duration of 1.4 ms, a focal size of 350 µm and a frequency of 14 Hz, the minimum pulse energy required to weld the cap to the substrate is 1.3 J. The simulation results in Figure 3 reveal that the applied pulsed laser generates a melt depth of 120 µm on the cap. Therefore we can conclude that at a melt depth of 120 µm, the generated molten pool at the cap is big enough to merge with the molten pool created at the substrate. The merged molten pool is solidified after cooling down and the cap is welded to the substrate. As well, Figure 3 reveals a correlation between the melt depth and laser focal spot size. This result satisfies the prescribed laser focal size in laser welding literature in accordance with the cap thickness [14].

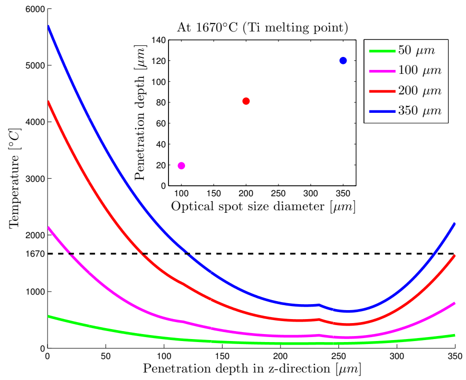

Figure 3: Correlation between pulsed laser focal spot size and the melt depth.

Simulation results in Figure 4 show a correlation between the melt depth and pulse duration. Figure 5 reveals the experimental results of the melt depth for the applied laser used in the simulation. Comparison of the experimental results with the simulation shows that the model is valid if the pulse duration is greater than 1 ms. For pulse duration of less than 1 ms, the generated heat vaporizes the titanium cap. As mentioned earlier the vaporization was not considered in our model and this disparity is expected to be seen.

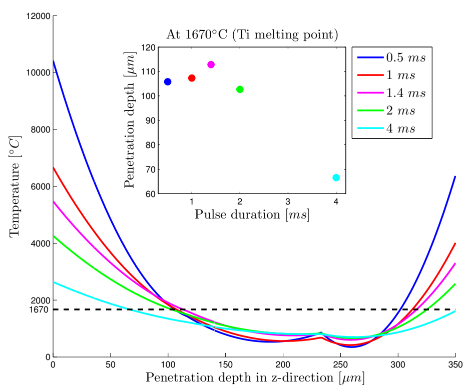

Figure 4: Correlation between laser pulse duration and the melt depth.

Figure 6 reveals the temperature gradient in the substrate which determines what distance from the heat source the MEMS device can be mounted. It can be seen that for the laser with a focal size of 350 µm at a distance of 450 µm from the laser heat source, the temperature on the substrate drops to 100ºC and the MEMS device can be safely mounted beyond this point.

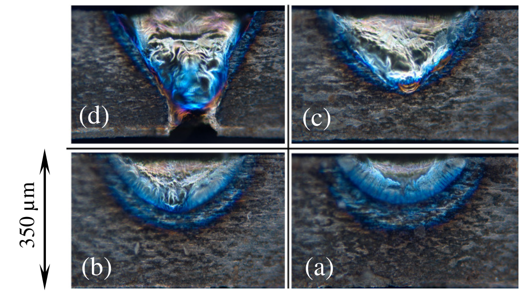

Figure 5: The melt depth generated by the applied pulsed laser with pulse duration of (a) 4 ms (b) 2 ms (c) 1.4 ms and (d) 1 ms.

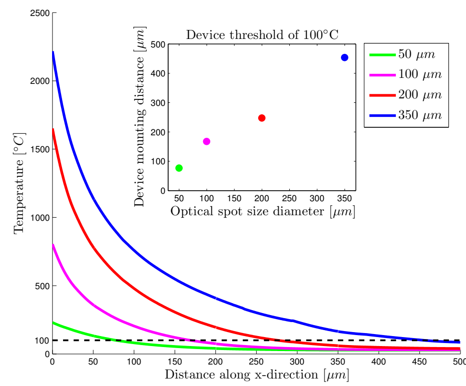

Figure 6: Temperature gradient of the substrate from the laser heat source for different focal spot size.

4 FABRICATION AND EXPERIMENT

To verify the proposed packaging method and its functionality on MEMS devices, an AFM tip was packaged on a titanium substrate. The device tested is a self-actuating self-sensing AFM cantilever tip (MPA-41100-S, Veeco Instruments). To communicate with the device, we designed and fabricated gold-ceramic-titanium or GCT feedthroughs on the substrate. The device was mounted and wire-bonded to GCTs, see Figure 7. By measuring the resonant frequency and quality factor before and after packaging as shown in Figure 7, it is determined that the applied technique has no effect on the packaged device or GCT feedthroughs. The laser system used in this experiment was a Nd:YAG pulsed laser with 1064 nm wavelength. Table 1 shows the laser parameters.

Laser Spot		**Seam Welding**	
Energy per pulse	1.3 J	Welding speed	0.85 mm/s
Peak power	1.3 KW	Focal spot size	300 µm
Pulse duration	1 ms	Pulse frequency	14 Hz

Table 1: Pulsed laser parameters.

4.1 Hermiticity

The hermiticity of the packaged device was measured by helium leaking rate test based on MIL-STD-883E standard. The helium leak detector used in this work was an Alcatel ASM 142, which measured a leaking rate of 3.45×10^{-10} atm.cc/s for a volume of 0.18 cm^3.

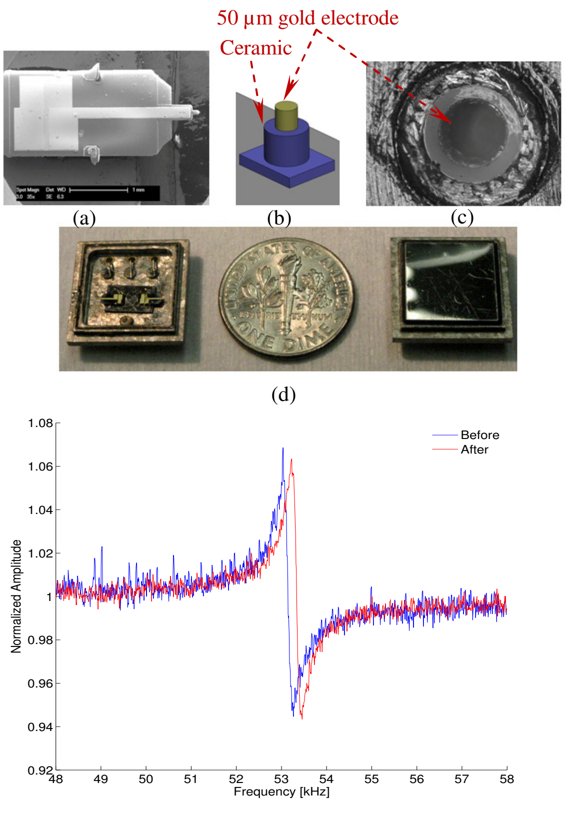

Figure 7: (a) AFM tip (b) designed GCT (c) fabricated GCT (d) the packaged AFM (e) resonance frequency of the AFM before and after packaging.

5 CONCLUSION

The new packaging method was modeled, simulated, fabricated and experimentally characterized. The laser parameters were investigated to optimize the melt depth based on minimizing the generated heat. We combined titanium as a new material for packaging and YAG millisecond pulsed laser as a localized heat source to introduce a new packaging technique for MEMS on both the wafer and device scale. The proposed technique overcomes other packaging technique issues such a heat distortion and MEMS device damage from global heating packaging processes. The demonstrated packaging method applies directly to the titanium cap and substrate with no need of any interface material or films between them. This is considered a main advantage over current methods. Our packaging method provides low cost, fast operation and precision with low thermal distortion, as well as reliability and biocompatibility with MEMS devices. This technique can be applied to both titanium and silicon MEMS making it a potential bridge between silicon Bio-MEMS and biotechnology applications.

6 ACKNOWLEDGMENT

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