TRANSIENT CLOSED-LOOP HEATING FOR LOCALIZED MEMS BONDING

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ABSTRACT

We achieve practical closed-loop control of a microfabricated resistive heating trace in millisecond-scale transient regimes for MEMS local solder bonding. This is one or two orders of magnitude faster than previous implementations and may be competitive with laser assisted bonding. We also present simple theoretical models for analyzing these heaters, then identify and analyze a possible failure mode due to local thermal fluctuations in more complex heater traces. Together, these represent significant progress toward making resistive localized bonding for general packaging purposes practically feasible.

KEYWORDS

localized bonding, solder bonding, joule bonding, transient heating, temperature control, RTD, NTC, PTC

INTRODUCTION

MEMS and IC packaging, the process of attaching and integrating microfabricated chips to a larger structure to interface with the outside world, is often difficult and accomplished by a variety of methods. A large class of techniques is bonding of two chips or wafers face-to-face by applying pressure while thoroughly heating both, at which point their interfaces, if sufficiently clean, atomically join (e.g., eutectic bonding and anodic bonding) [1]. However, there exist applications that cannot withstand the required high temperatures, including polymer and biological devices, thin-film batteries, and iterative stacking of multiple chips. In these cases, a number of techniques have been proposed to limit heating to a only a small area of the chip [1][2].

These local bonding methods are typically similar to flip chip, microbump, and transient liquid phase bonding in that solder is fabricated on one chip, melted by some means, then bonded to another chip brought into contact. However, heat flow is limited to melt the solder but minimize temperature rise in the surrounding chip substrate.

This can be accomplished via, e.g., an on-chip resistive heater adjacent to the solder pads [1][2][3] (Fig. 1, "joule bonding"), which has achieved solder, Au-Si, and Si-glass bonds in 2 min to 5 min [1], and one work managed 0.25 s [3]. To date, these have only been made in simple line or circle geometries. Alternatively, a pulsed laser can melt the solder in nanoseconds to milliseconds (laser assisted bonding, LAB) [4][2], given complex equipment. To the best of the authors' knowledge, neither method has yet achieved accurate temperature control in millisecond time scales [5].

In this work, we demonstrate a resistive heating method that achieves this closed-loop temperature control and do so within in a competitive 10 ms to 1.0 s. We also investigate temperature control along heaters of arbitrarily complex shapes, then conclude that joule bonding has the potential to become a competitive bonding process.

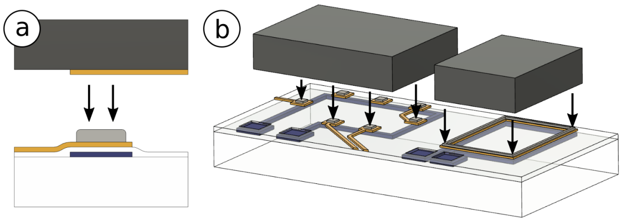

Figure 1: (a) Joule bonding uses a resistive heater (blue) to locally melt solder (gray) fabricated on metal pads (yellow). (b) This could bond chips for electrical interconnects or hermetically sealed cavities. In this work, we show how to build more effective resistive heaters.

METHODS

Average Temperature Control

First, we demonstrate a simple method to heat a thin film resistive trace on a flat substrate in closed-loop control. Putting electrical power into such a trace results in joule heating. If the trace changes resistivity with temperature (that is, it acts as a resistive temperature detector, RTD), then it can simultaneously act as heater and temperature sensor with no additional on-chip hardware.

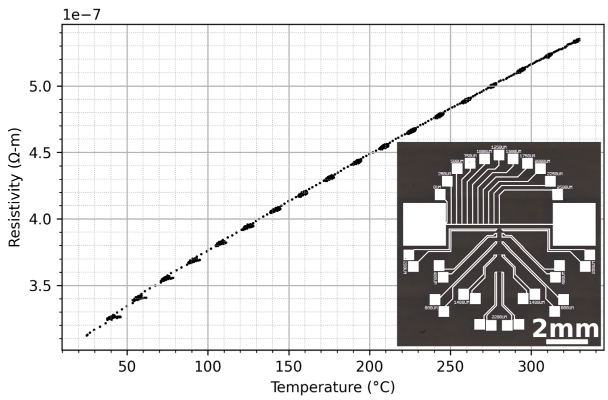

Figure 2: Resistivity of the annealed Ti/Pt film versus temperature, measured via a calibrated computer-controlled hotplate and 4-point resistivity test. Inset: stitched micrograph of a test device with a 5mm by 50µm heater trace, unused voltage probes above, and 4-point resistivity probes for substrate temperature measurement below.

To accomplish this, we evaporated and patterned via liftoff 20 nm Ti / 80 nm Pt (widely used in heaters and RTDs) on a 0.7 mm fused silica wafer (for its low thermal conductivity, simplifying these tests; we save materials with higher thermal conductivity for future work), then annealed the film at 450 °C for 1 h. The device and measured resistivity vs. temperature curve are shown in Fig. 2. The device was placed on top of a large aluminum block in 21 °C atmosphere for all tests.

Next, we created a control circuit as shown in Fig. 3. A microcontroller varies a DC current source that regulates current through the resistive heater trace load (connected via two micromanipulator probes), and the current through and voltage across the load are measured simultaneously. The microcontroller continually (at about 20 kHz) computes the load resistance (and temperature, via a linear fit to the data of Fig. 2) then changes the current to maintain a desired temperature. This is the heart of the bonding process: the microcontroller can now make the heater follow arbitrary temperature profiles (however, in this work, we limit ourselves to step functions for simplicity).

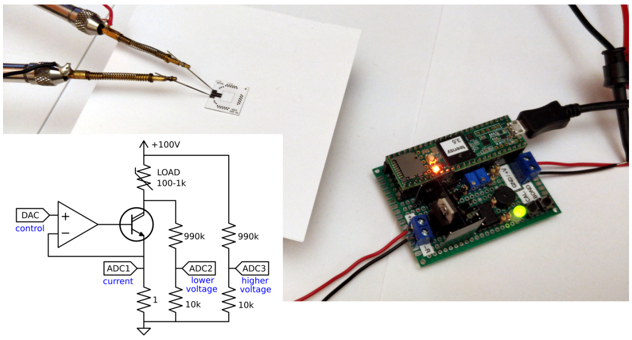

Figure 3: Left, circuit schematic. Right: the circuit connected to a test device (slightly different than in Fig. 2). Note this setup is much simpler than the equipment required for most other bonding methods—in fact, it should be possible to fabricate this control circuit on the chip-to-be-bonded itself, perhaps for self-assembling microrobotics.

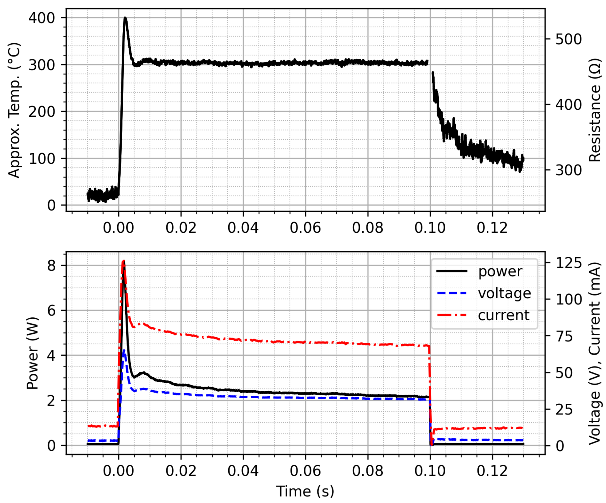

Figure 4: Temperature, resistance, power, voltage, and current in a simple rectangular heating trace at 300°C for 0.1s. Note that the temperature stabilizes within 10ms.

Finally, we use this controller to heat the 5 mm long by 50 µm wide rectangular trace described in Fig. 2 to 300 °C (chosen to demonstrate the ability to reach higher temperatures than the melting points of most solder alloys) for 0.1 s, with results graphed in Fig. 4. The desired temperature is achieved in less then 10 ms and maintained for the full duration of the 0.1 s heating time. There is no inherent limit on the heating time save for the heat the sample can withstand. The initial temperature overshoot is caused by control loop mistuning; an improved implementation may be able to achieve a setpoint within one millisecond or better.

To demonstrate the main advantage of local bonding (namely, a low substrate temperature), we also measure the transient temperature on the surface of the substrate some distance away from the rectangular heater, with results graphed in Fig. 5. The heater was engaged for 1.0 s instead of 0.1 s so that the temperature rise in the substrate would be sufficiently large to measure.

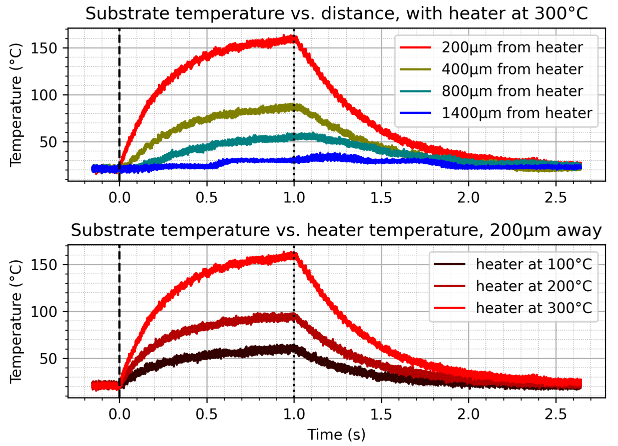

Figure 5: Temperature rise on the substrate surface at assorted distances from the line heater center at various temperatures, measured via monitoring 4-point resistances using the device shown in Fig. 2. The blue curve for temperature at 1400µm is jagged due to oscilloscope quantization.

To use this heating system for joule bonding as in [1][2] or illustrated in Fig. 1, the heater would be covered by a layer of insulating oxide on top of which metal pads (for solder adhesion and a wiring layer) and solder itself were microfabricated, and real devices could be complicated by other features. Easily designing these systems requires that power input and substrate temperature rise can be estimated accurately. Next, we present a method for this.

Transient Heating Mathematical Model

We want to model the transient behavior of this system. To do so, we take the simplified case of a heater trace of width W on top of an infinitely thick substrate with thermal conductivity k and volumetric heat capacity c, as shown in Fig. 6, and consider heat transfer in the 2D cross section. This is a refinement of the classic solution for heat transfer into a "semi-infinite solid" (for which $W = \infty$) as derived in, e.g., [6] and applied to local bonding in [3].

For large W/x_t (as in Fig. 6), the analytic solution to the semi-infinite solid applies. For small W/x_t, [6] (§13.5) gives an analytic solution for the closely related case of a circular heater cross-section. For intermediate W/x_t, we simulated the model via ANSYS. These results approximately match our experimental tests in Figs. 4 and 5.

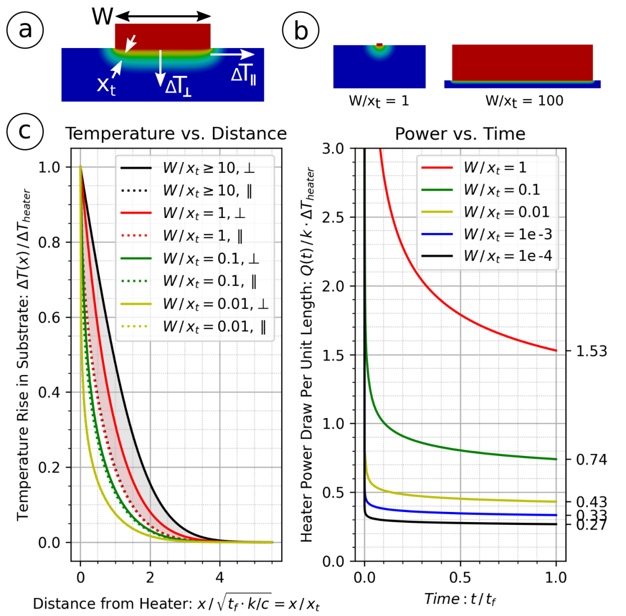

Figure 6: 2D transient behavior of a rectangular heater on a semi-infinite substrate as in (a). The heater turns on at time $t = 0$ and instantly reaches a constant temperature ΔT_{heater} above ambient. In (c), the left graph shows the temperature rise $\Delta T(x)$ in the substrate at time $t = t_f$, while the right graph shows the power output (per unit length of heater) into the substrate by the heater between times 0 and t_f required to maintain its constant temperature. Results are given in terms of the ratio W/x_t, the ratio of heater width to the approximate distance heat diffuses in time t_f as visualized in (b). Note that $\Delta T(x)$ varies with the direction: we give results for $\Delta T_\perp(x)$ directly below the heater and $\Delta T_\parallel(x)$ along the surface of the substrate as defined in (a).

This model should extend to the full bonding process. Typically, $x_t \approx 1$ mm, in which case the effect of any insulation, traces, or solder on top of the heater, likely < 5 µm thick, can be ignored. Solder should approximate the temperature of the heater as the Biot number of the solder-heater stack is small. Air convection is negligible because the Rayleigh number of the system is low [7]; instead, the air can be treated as a second semi-infinite solid above the heater (with less heat loss than to typical substrates). When a chip to bond is placed on top of the solder, it might be modelled as yet another semi-infinite solid. Note this will change the power input significantly, which helps motivate the consideration of varying local temperatures.

Local Temperature Fluctuations

So far, we have controlled only the average temperature of a heater trace. If the heater trace width varies, or the substrate can conduct more heat away at some point (e.g., at corners), the trace temperature might vary locally (presumably to the detriment of the bonding process). [1] finds the temperature variation in a straight heater under constant voltage in steady state. We would like to extend this to the transient case with more complex heater geometries. We began by experimentally heating the trace of varying width shown in Fig. 7, which we measure in 18 discrete segments.

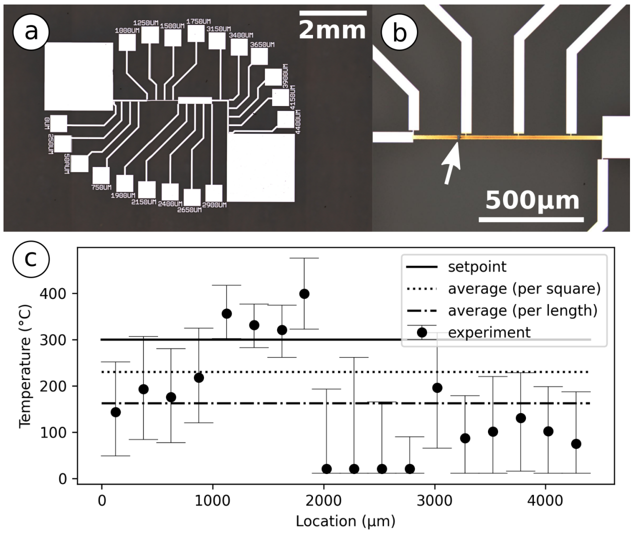

Figure 7: (a) Heater trace of varying widths (50, 20, 200, and 50 µm) with voltage probes to measure resistance of individual segments via 4-point test given the known current. (b) High current causes the thinnest part of the trace to yellow and eventually vaporize, creating a gap and open circuit (marked by an arrow). (c) Measured temperature distribution along the heater when driven to a nominal 300°C.

The controller maintained a setpoint of 300 °C according to our previous scheme, but the measured data, based on summing local power dissipation, was consistent with a $\approx 50\,\Omega$ series resistance and actual 220 °C heater temperature. We note this temperature—calculated from the total resistance—is the average temperature per resistance square. The more useful average, i.e., over distance along the trace, was calculated to be an even lower 160 °C. We note there is some inaccuracy in our original measurements but believe the qualitative behavior is accurate.

We can explain these results with two effects: local variation can result in large temperature swings, further affecting the overall control, and sufficiently high power can melt the trace. We write the heat equation for any point along the heater with three terms: the joule heating power input, thermal diffusion into the substrate/environment, and thermal diffusion along the heater:

$$\frac{\partial T}{\partial t} = \underbrace{\frac{I^2(\beta T + \alpha)}{cA(x)^2}}_{\text{joule heating}} - \underbrace{\frac{H(x)\cdot(T - T_\infty)}{cA(x)}}_{\text{substrate diffusion}} + \underbrace{\frac{k}{c}\frac{\partial^2 T}{\partial x^2}}_{\text{heater diffusion}} \qquad (1)$$

where $T(x)$ is the instantaneous temperature (units K), I is the current through the heater (A), $\beta T + \alpha$ is the electrical resistivity (as a function of temperature) (Ω m), c is the volumetric heat capacity (J/m^{3}K), k is the thermal conductivity (W m^{-1} K), A is the heater cross-sectional area (m^2), T_∞ is the ambient temperature (we assume $T > T_\infty$), H is the heat transfer coefficient per unit length from the heater to its surroundings (W m^{-1} K), and x indicates distance along the heater (m). T, A, and H can vary with x. As in Fig. 6, H varies with time (as well as position), but this change is slow compared to heating time constants.

The joule heating term increases the local heater temperature, the substrate diffusion decreases the temperature, and the heater diffusion tends to even out temperature differences along the heater. However, these all happen at different rates, and the behavior of temperature T over time is decided by these relative rates. For local bonding, because we explicitly design the system such that heat does not transfer far into the substrate, we assume $\frac{k}{c}\frac{\partial^2 T}{\partial x^2} \approx 0$. Thus, we can treat each point on the heater as essentially independent: in this transient regime, the local thermal behavior is controlled solely by the current, cross-sectional area A, substrate heat transfer H, and resistivity vs. temperature relationship. Rewriting (1) at $\frac{\partial T}{\partial t} = 0$,

$$T_{\text{equilibrium}}(x) = \frac{A(x) \cdot H(x) \cdot T_\infty + I^2\alpha}{A(x) \cdot H(x) - I^2\beta} \tag{2}$$

Because the denominator of this equation must be positive to be physically realistic, there is a maximum current $\sqrt{AH/\beta}$ beyond which the temperature will exponentially rise to infinity, melting and eventually vaporizing the heater at that point (incidentally, this is how sacrificial fuses work). This is particularly problematic because the current is constant along the heater, so if $A \cdot H$ varies too much, this thermal runaway is unavoidable. We can calculate the sensitivity of $T_{\text{equilibrium}}$ to $A \cdot H$:

$$\frac{\partial T_{\text{equilibrium}}}{\partial(A \cdot H)} = -\frac{I^2(\beta T_\infty + \alpha)}{(A \cdot H - I^2\beta)^2} \tag{3}$$

For example, in our first experiment of Fig. 4, this predicts the local equilibrium temperature might change several hundred degrees C if H varies by 50%, which may happen as a chip to bond is brought into contact. This is problematic as-is, but solutions exist, as detailed in the next section.

DISCUSSION

We have shown how a resistive heater can be controlled (on average along its length) to a given temperature within milliseconds with minimal temperature substrate rise, and in doing so we make joule bonding significantly more competitive. However, we have also shown that local temperature fluctuations along a heating trace can be extremely large.

To fix this, area A could be varied along the heater to compensate for varying H, as has been done for some MEMS hotplates. However, this is unreliable as H changes over time in the transient regime. Instead, according to equation (3), we propose using a heater material with a negative temperature coefficient (NTC) β. A sufficiently steep resistance decrease around $T_{\text{equilibrium}}$ will increase the denominator of (3) and result in arbitrarily small temperature fluctuations. One candidate material might be the widely used indium tin oxide (ITO), for which one group has reported a near-ideal NTC curve [8]. In fact, a sufficiently good material might minimize the dependence on $A \cdot H$ such that no external closed-loop controller is required! A similar effect is already used in self-regulating macroscopic heaters with ceramic positive temperature coefficient (PTC) heating elements whose resistance sharply increases near their curie temperature (and, with a different heater configuration, perhaps these materials could work here).

Thus, while there is still work to be done, we believe there are no fundamental thermal issues so long as material challenges can be solved, and we believe joule bonding has significant potential as a local bonding method.

ACKNOWLEDGEMENTS

Thanks to the Berkeley Marvell NanoLab staff (especially Ryan Rivers and Joanna Bettinger) for fabrication discussion and assistance, Anju Toor for patience, and Liwei Lin for brief discussion.

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