Turkish Journal of Electrical Engineering & Computer Sciences
http://journals.tubitak.gov.tr/elektrik/
Research Article
Turk J Elec Eng & Comp Sci
(2016) 24: 3513 – 3523

doi:10.3906/elk-1407-109

Experimental characterization of wafer probe burn

Baha ZAFER[1,*], **Bahadır TUNABOYLU**[2]
[1] Department of Mechanical Engineering, İstanbul University, İstanbul, Turkey
[2]Department of Industrial Engineering, İstanbul Şehir University, İstanbul, Turkey

Received: 16.07.2014 • **Accepted/Published Online:** 11.05.2015 • **Final Version:** 20.06.2016

Abstract: The probing test is a typical quality control method for individual chips on a wafer. This study investigates the cantilever wafer probe current carrying capacity along a probe body in order to model the probe burn phenomenon by using experimental techniques and numerical simulation. The standard measurement approach used in the test industry is conducted to define the mechanical degradation of the cantilever probe on the wafer card and temperature distribution along the probe body is conducted using a conduction heat transfer equation via computational discretization. Maximum current carrying capacity is defined and the probe burn phenomenon is observed at the tip region of the tungsten–rhenium cantilever probe due to effects of Joule heating for both experimental and numerical results. Reasonably good agreement is observed between experimental and computational results.

Key words: Probe burn, wafer level test, cantilever probe, Joule heating

1. Introduction

Recent advances in semiconductor process technologies have enabled the design of complete electronic systems on a single chip. In order to handle the complexity and satisfy the increasing demand for a shorter time to market, design engineers typically use different experimental and computational approaches in their designs, especially for structural analysis and thermal management [1]. The wafer level test is the first step in the manufacturing test process, where the chip in bare wafer form is tested by using the input/output (I/O) terminals of the chip for manufacturing defects. The devices are subjected to standardized parametric and functional tests such as electrical excitations and thermal cycles [2]. In the wafer level test, an individual chip is tested using a probe card with probe card needles as shown in Figure 1.

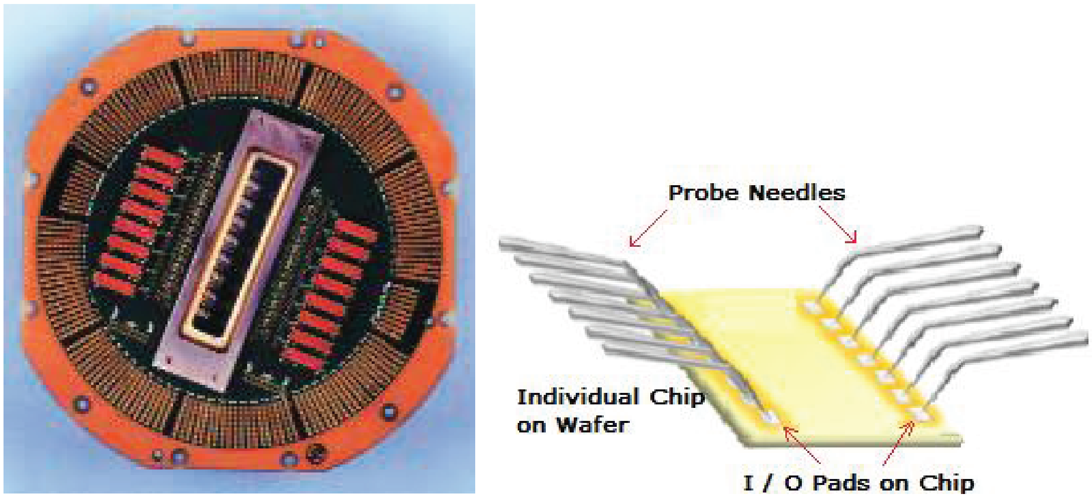
The wafer contact is becoming an important issue because of the difficulty in controlling the applied probe force on a contact pad and power delivery to the chip through the probe from the tester generating conductive thermal effects due to Joule heating. Test system performance is dependent on the ability of probes to carry required test current to the chip. Besides the contact force and the test direct current/pulsed currents, the material properties and geometry of the probe card needles also play important roles in wafer level testing.

In this paper, a cantilever beam was selected as the probing technology. An experiment is conducted for cantilever wafer probes in order to predict current carrying capacity and mechanical degradation relation in the case of investigating probe burn effects. A numerical simulation is carried out to investigate temperature distribution along the probe body in which location the temperature exceeded the melting point of tungsten–rhenium (W-Re). In addition, the different geometrical factors of the probing needle, as shown Figure 2,

---

[*] Correspondence: baha.zafer@istanbul.edu.tr

including needle base diameter, beam length, taper length, and tip diameter were measured using a high resolution microscope.



(a)

(b)

Figure 1. Images of a) probe card for higher pin counts and b) detailed view of cantilever probe needles and wafer pad contacts.

2. Probe burn phenomena

A probe will burn during the wafer test when its probe current carrying ability (I_{max}) is exceeded. The maximum allowable probe current carrying capability is a function of probe material, probe wire diameter, and probe tip diameter. In addition, the continuous (steady state) or pulsed currents are important parameters for the study of probe burn.

Probes are usually the weakest link in the test architecture and therefore first to burn during testing due to the constriction resistance. Therefore, in many applications the crucial point is how much current can be handled by a cantilever probe tip. Increasing wafer probe current beyond its limit can drastically reduce life span by deforming or burning the probe tip. Experimental study results showing probe burn locations [3,4] for vertical and cantilever types of probes are shown in Figure 3. The current constriction happens in the thin buckling beam section for vertical probes and at the tip section for cantilever probes.

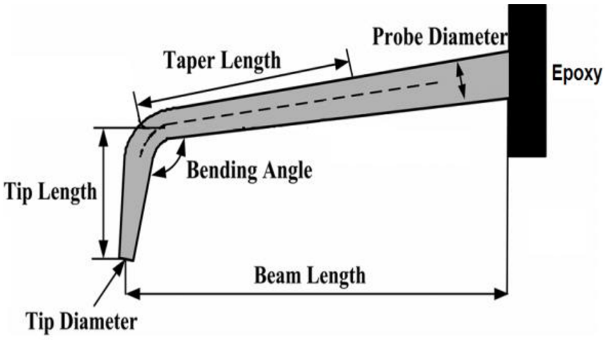


Figure 2. Geometry of the cantilever probe needle.

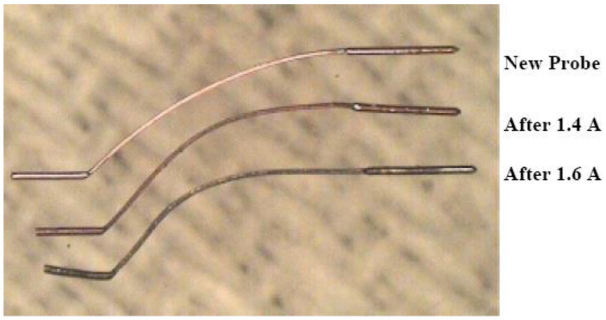


Figure 3. Probe burn effects on the vertical probe at the middle curved section of the probe [3,4].

When an electrical current passes through a cantilever probe during the wafer level test, it heats the probe through a process known as Joule (or I^2R) heating [5–10]. Joule heating is an energy dissipation phenomenon commonly observed in electrical current carrying conductors. It converts irreversibly electrical energy to thermal energy. Some of this heat dissipates through conductive and convective heat transfer to the wafer, the probe card support mechanicals, and the ambient air. With a sufficient increase in current flow through the cantilever probe, the heat generated will exceed the natural heat dissipation and the probe temperature will increase. Eventually, the temperature of the probe reaches a critical value at which mechanical strength diminishes and plastic deformation begins as shown in Figure 3. This decreases the contact force, which adversely affects electrical contact resistance. This, in turn, can generate unreliable test readings and wafer yield loss. The maximum allowable loss of contact force due to current passing through a deflected probe is 20%, as a generally accepted criterion in the wafer test industry [11].

3. Experimental setup

The measurement of current carrying capability (CCC) for wafer probes is a critical parameter for probe cards. The CCC depends on many parameters such as probe tip diameter, ambient temperature, thermo-physical properties of material, the duration of applied current, and the contact resistance at the probe tip-bond interface. For practical reasons in wafer testing, the critical steady state current value can be defined by the level of mechanical degradation of a probe. There will be no damage to the elastic properties of the probe below this critical value. The failure signature chosen for the CCC value is a permanent reduction in force in the probe. As a definition, it is assumed that the criterion for the maximum current capability is a 20% drop in probe force.

The 20% force reduction method is applied to the force measured for a new probe prior to exposure to steady state current. In practice, the force of the probe at nominal overdrive, which means the vertical distance measurement from the first contact point of the probe to the device surface, actually increases as the current is first applied.

The experimental setup for CCC measurement is shown in Figure 4. The basic system consists of a force transducer as a balanced contact force (BCF) station mounted on a vertical micrometer stage and a fixture that captures the probe between two conductive contacts. A constant current power supply and current/voltage meters complete the setup.

The measurement methodology will be identical to those used in the industry [11]. The measurements will be first carried out under dc conditions and the test procedure can be described as follows:

i. Apply an initial deflection of different overdrive for different probe base diameters. Record the force on the probe.

ii. Initialize the dc current supply (at 0) and set the voltage.

iii. Turn current OFF and wait 1 min to allow the probe to cool.

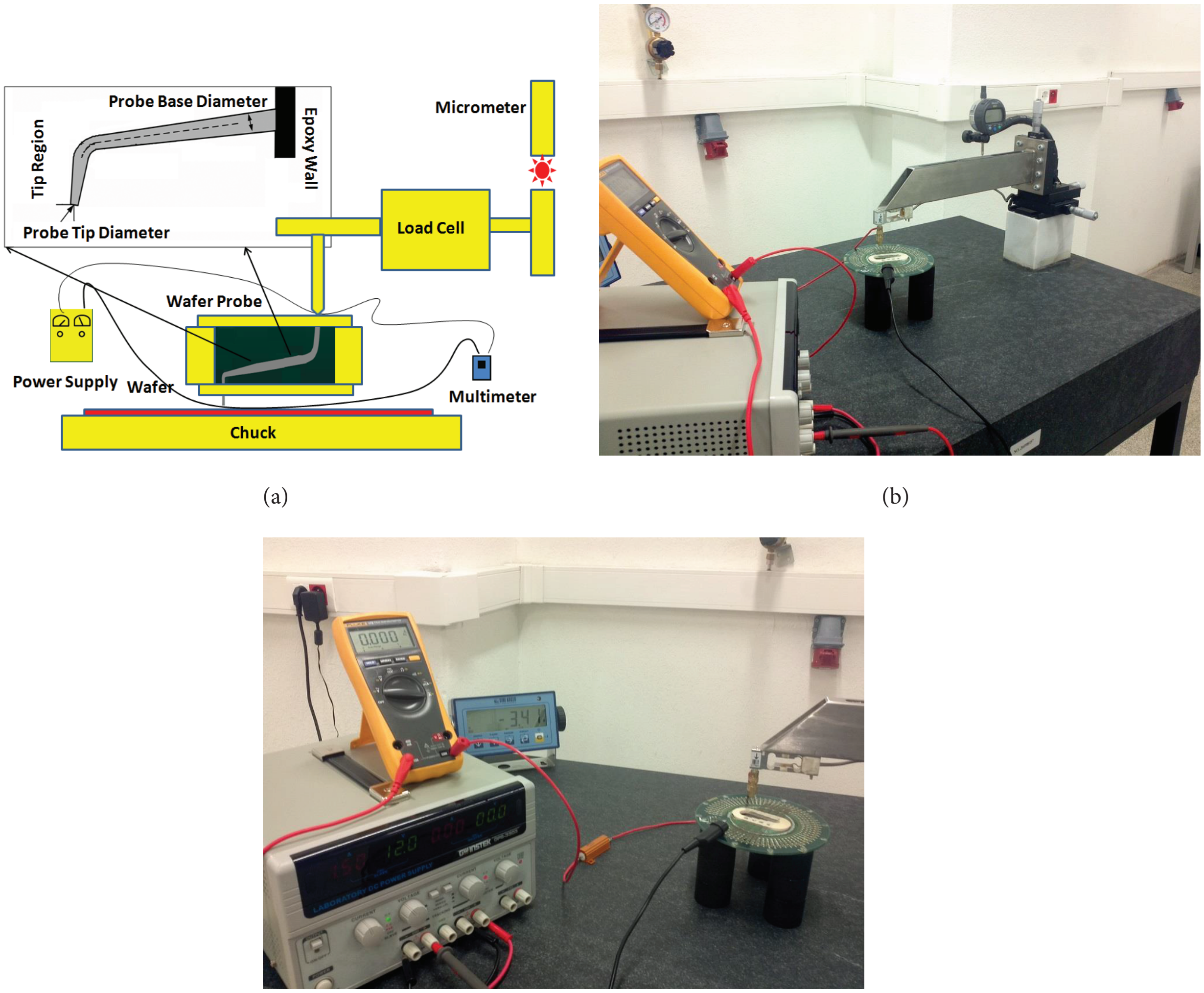
iv. Measure height of probe at the end of each current input using micrometer.

v. Increase the continuous current in 100 mA increments from initial state, $I_{init} = 0$ and the current is applied for 1 min and turn it off. Record the force after stabilization.

vi. Go to the next increment (100 mA). Repeat step v.

vii. Continue the test up to the probe softening stage.

viii. Repeat the test for 3 probes.



(a)

(b)

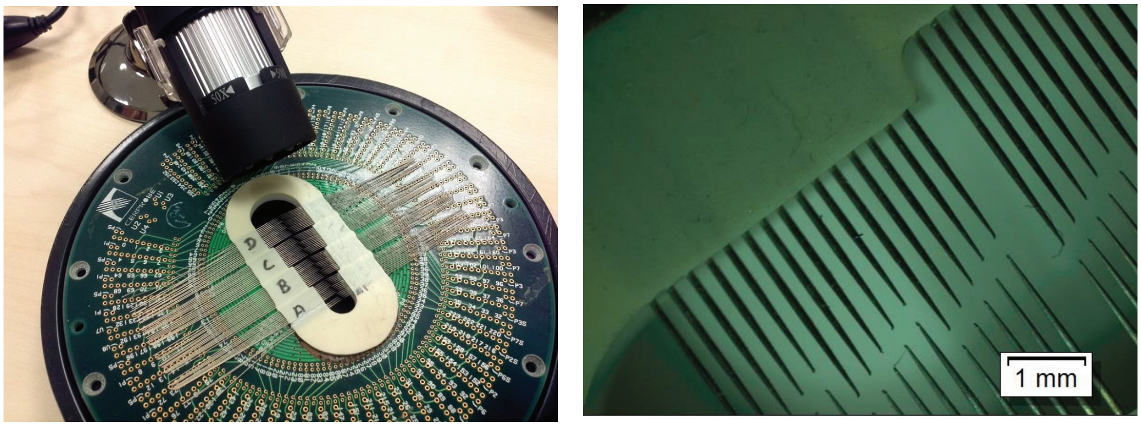
(c)

Figure 4. Experimental setup in general view in (a) and detailed view in (b) and (c).

This procedure will be repeated for pulsed current settings for typical duty cycle 20% with total cycle 100 ms in the second experimental set. Another duty cycle can be selected depending on the probe design and probe card technology studied. The cantilever wafer probe baseline material is tungsten–rhenium (W-Re) in this experimental study. Probe cards are procured from the card vendors. The test setup will be established at the host institute, using a power supply, micrometer, and transducer.

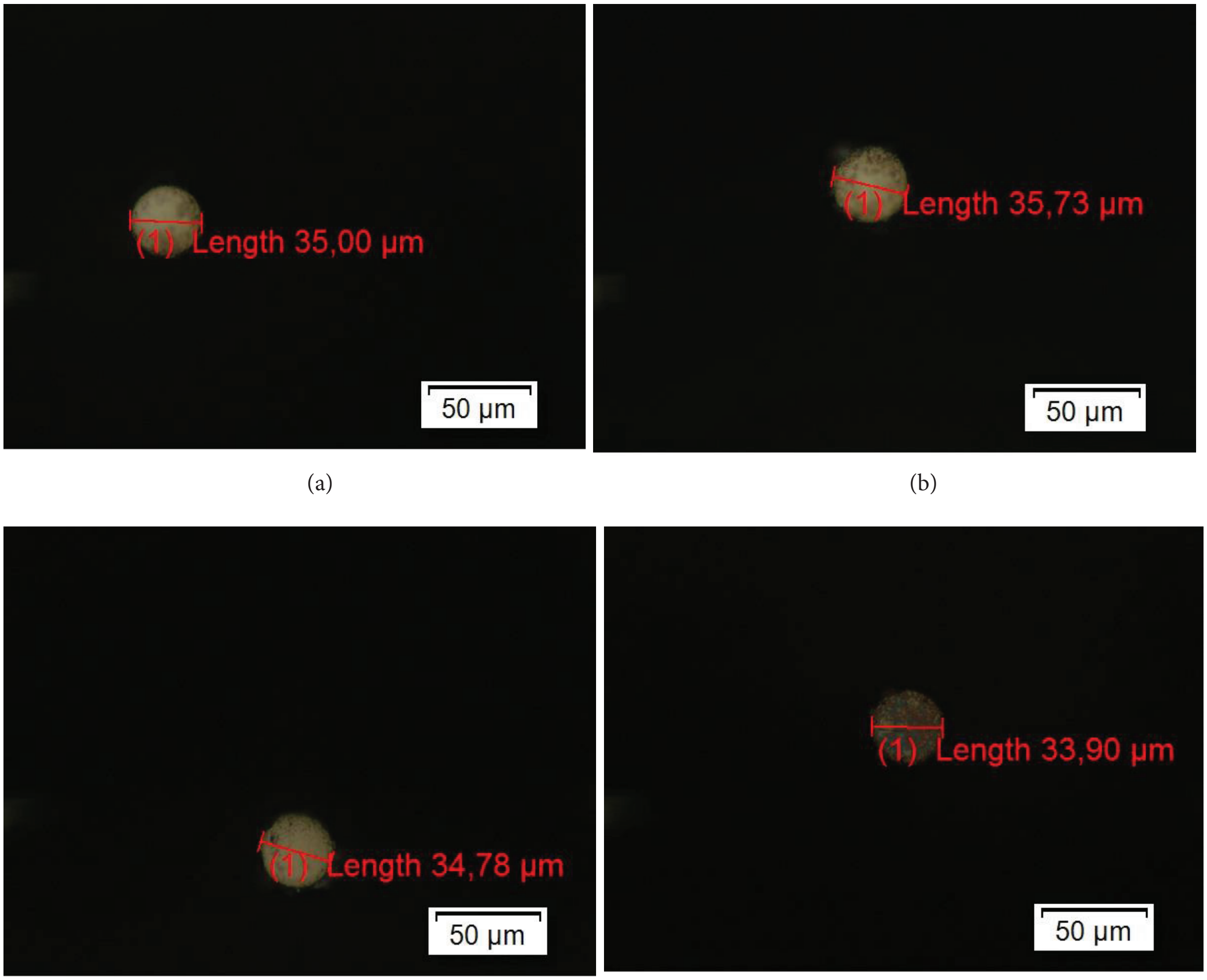
A wafer probe card with a cantilever type needle is investigated in this study as shown in Figure 5. The ability of probes to handle current is extremely important in many probing applications. Forcing probes past their boundaries of current can not only damage the probe card but also decrease the life of the probes. In order to avoid these problems, the current carrying capacity of the probe must be measured.

The dimension of the probe is measured by using a high order optic microscope. In Figures 6a–6d, the probe card is shown.



(a) (b)

Figure 5. General view of the probe card is shown in (a) and the detailed view in (b).

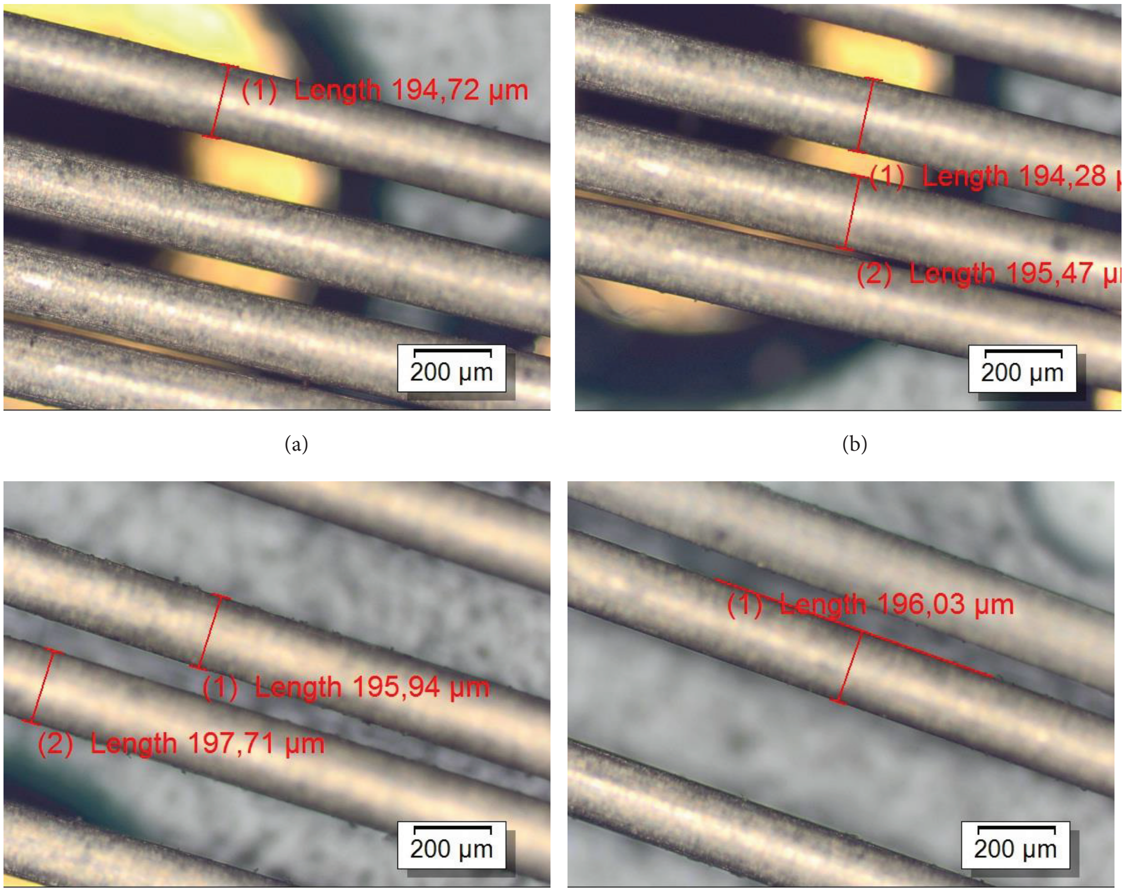


(a) (b)

(c) (d)

Figure 6. Measurement of tip diameter of the cantilever wafer probe.

For the experiments, epoxy-ring cantilevered probe cards designed for fine-pitch devices were built using small-diameter W-Re flat-tipped probes. The probe cards were built with the best-known practices for use in a standard tester/prober setup on a high-volume production test floor. The tip dimension of the cantilever probe is defined as 35 mu m by using a high order sensitive microscope and body diameter is 195 mu m as shown in Figure 6. The bending region of body diameter before the tip is obtained as 65 mu m in Figure 7. As depicted in Figure 8, the junction region of the body and tip is also measured in order to define diameter. The bending region diameter is 66 mu m.



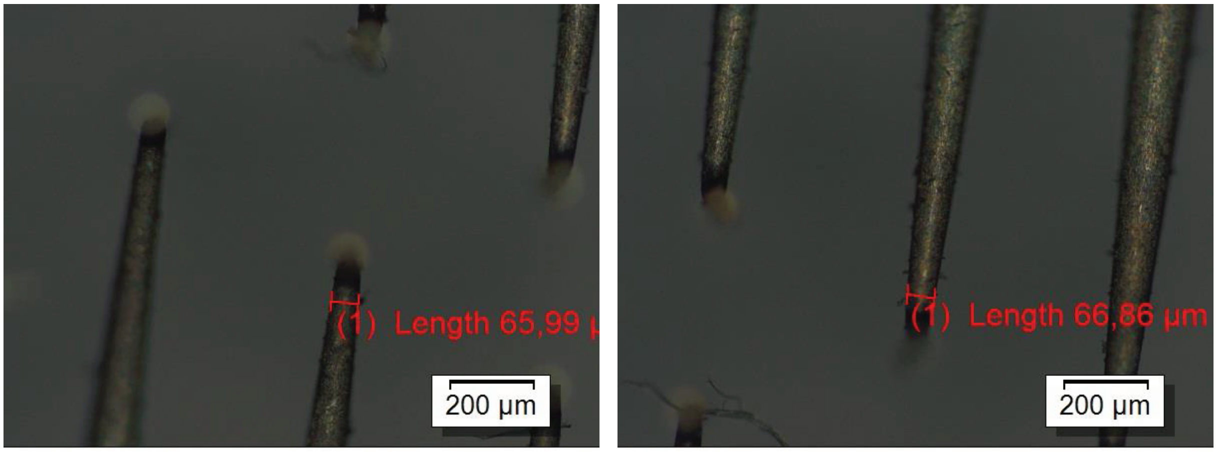
(a) (b)

(c) (d)

Figure 7. Measurement of body diameter of the cantilever wafer probe.

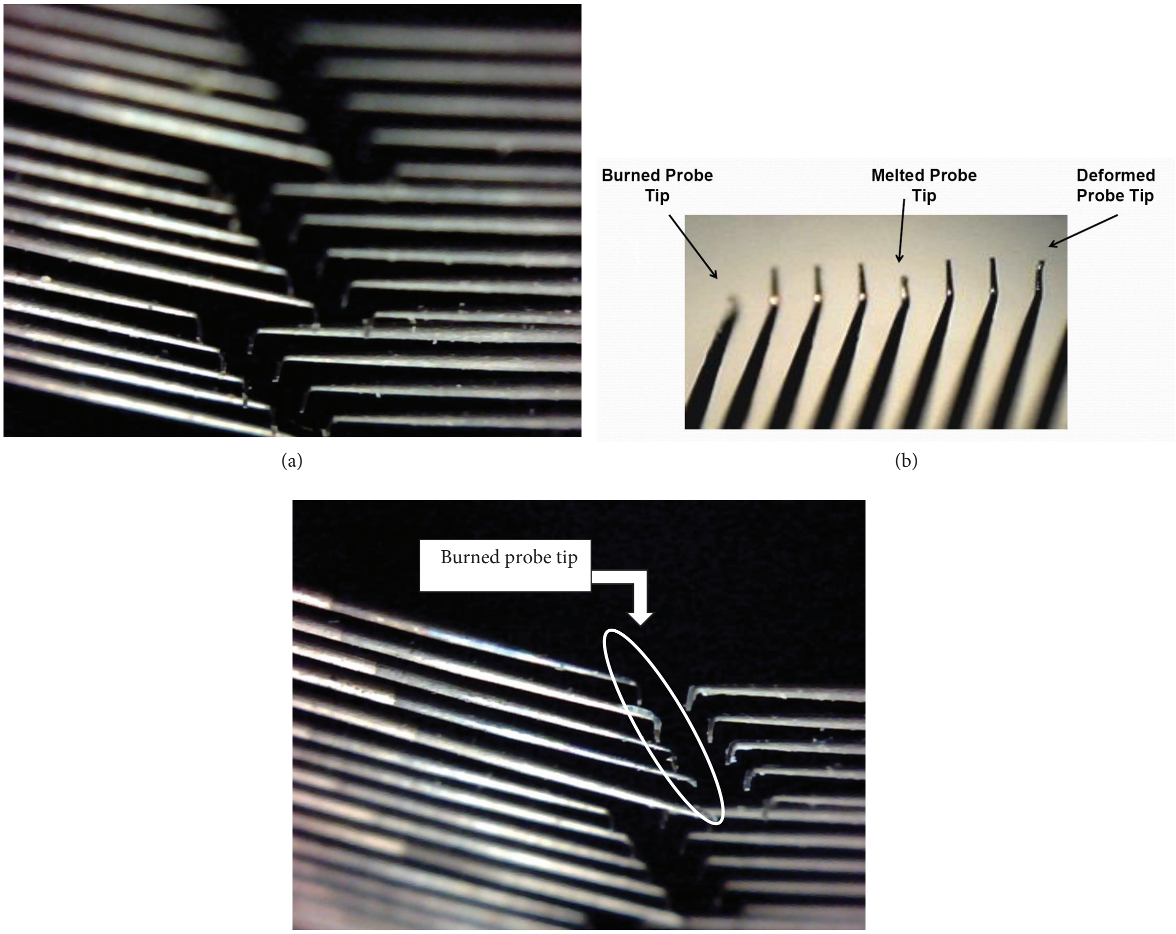
The conducted experimental results are given in qualified and quantified sense. The wafer probe card is investigated under an experimental setup using the procedure mentioned before in detail. The burned probe tip region is shown in Figure 9a in qualified sense and applied force vs. applied current results are shown in Figure 10.

Maximum current carrying capacity is defined under different probes and the average value is 1.9 A. As depicted in Figure 10, in the case of the 4th probe, mechanical degradation gets higher when the applied current increases and suddenly decreases nearly 1.3 A. In the case of the 1st and 3rd probes, they maintain their responses gradually while applied current is increasing, and then mechanical degradation dramatically drops. Therefore, in that case, the probe burned tip type phenomenon is observed. The maximum current carrying capability is computed as follows:



(a) (b)

Figure 8. Measurement of bending region diameter of the cantilever wafer probe.



(a) (b)

(c)

Figure 9. (a) Nontested cantilever probe is shown. (b) Detailed view of cantilever probe after experimental effects is defined more clearly such as deformation, melting, and burn, respectively shown from right to left. (c) The left side probes are tested and deformation is obtained under the effects of Joule heating.

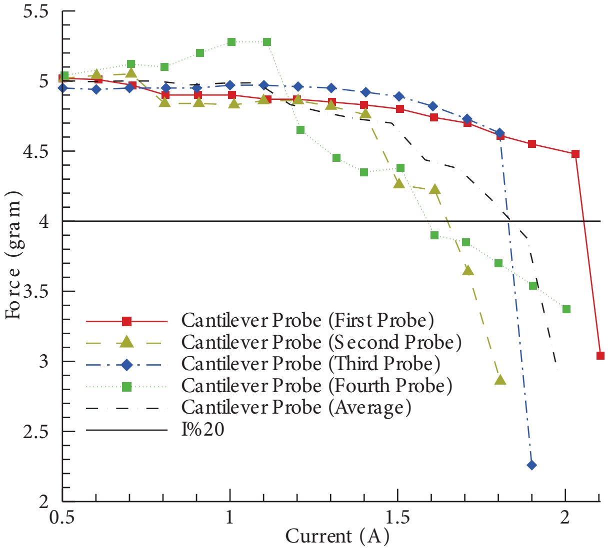


Figure 10. Experimental results showing the relation between the mechanical degradation (force) and the applied electrical current (A) for cantilever wafer probes.

$$I_{\max} = \frac{[Average\,(I_{\%20})]}{2} \tag{1}$$

From Figure 10, average $I_{\%20}$ is defined 1.9 A and using Eq. (1) I_{max} is computed as 0.95 A, which is the maximum current value protecting the probe tip from deformation and melting in order to keep going the wafer probe card in operations.

4. Computational modeling

In solid regions, the general form of the energy transport equation used by commercial finite volume solvers has the following form [12]:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\vec{v}\rho h) = \nabla \cdot (k\nabla T + q_r) + S_h, \tag{2}$$

where ρ is the density and k is the thermal conductivity. h is the sensible enthalpy defined as

$$h = \int \overset{T}{\underset{T_0}{\lim}} c_p dT \tag{3}$$

The terms on the right-hand side of Eq. (2) are the heat flux due to conduction; q_r is radiation heat flux and S_h is volumetric heat source. The second term on the left-hand side of Eq. (2) represents the convective energy transfer and $\vec{v}$ is the motion fluid particles. As an assumption, the cantilever probes can be operated in either liquid or gaseous media. However, due to the very small size (i.e. order 10^{-6}) and high volumetric rate of heat energy generation due to Joules heating, the heat conduction within the cantilever probe structure will dominate the heat transfer upon liquid or gaseous media via convection or radiation. Thus, the heat conduction is the most relevant mode. Neglecting the convection and radiation modes of heat transfer and considering Joule heating as the only energy conversion, Eq. (2) can be modified by using Eq. (3),

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + S_h \tag{4}$$

This is the most general three-dimensional form of heat conduction equation including thermal energy generation. Assuming the thermal conductivity is a weak function of temperature, Eq. (4) in Cartesian coordinates can be given as:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t}-\frac{S_h}{k}, \tag{5}$$

where $\alpha\,(=k/\rho c_p)$ is the thermal diffusivity and c_p is specific heat coefficient. This equation is also known as the heat diffusion equation. The thermal diffusivity is the controlling transport property for transient conduction. The higher the value of thermal diffusivity the faster the system will reach its new temperature equilibrium. Since the value of thermal diffusivity is very high for the cantilever probe, the system reaches steady state very rapidly in the computational case. Therefore, the first term on the right-hand side of Eq. (5) goes to zero. The negative sign in Eq. (5) can now be omitted because traditionally this sign was used to indicate the heat loss in a system, but in our case heat is generated.

To model the thermal conduction effects between the cantilever probe and wafer pad, a solver user defined function (UDF) is programmed that uses Joule heating formulation as the source term. Heat flux values are computed corresponding to applied current values (i.e. $I_{app.}$ in amperes), which are imposed from the tester according to following formulation:

$$S_h=\frac{V_b^2}{\rho_e L^2}=\left(\frac{I_{app.}}{A_{tip}}\right)^2\rho_e, \tag{6}$$

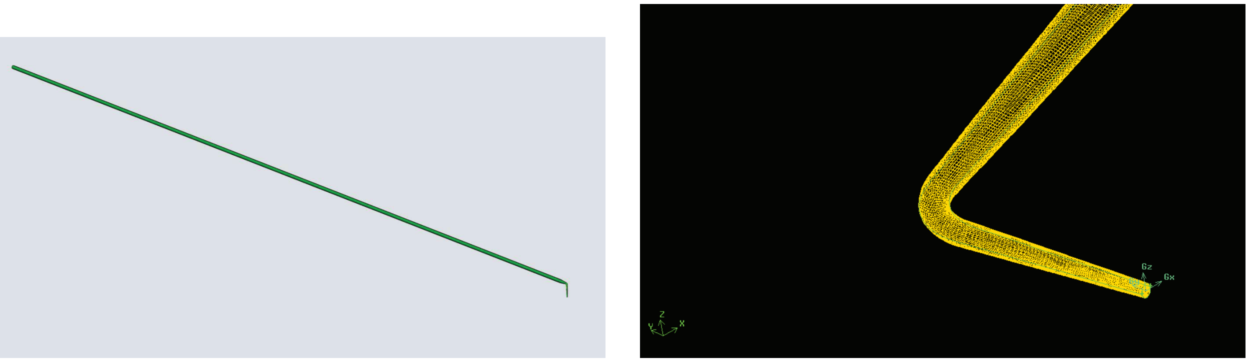
where V_b is applied electrical potential and L is length of the cantilever probe. A_{tip} is the tip area of the wafer probe and electrical resistivity ρ_e is an inherent property of a material to resist the flow of electrical current through it by means of producing electrical resistance. Electrical resistivity is independent of material geometry and depends on temperature, given as

$$\rho_e\left(T\right)=\rho_{e,0}\left[1+\eta\left(T-T_0\right)\right], \tag{7}$$

where η is the temperature coefficient of resistivity and $\rho_{e,o}$ is the electrical resistivity defined at reference temperature T_0. In deriving the above equations from Eq. (2) to Eq. (7) certain assumptions were made. It is assumed that adiabatic condition exists at the base and the temperature of the base is unchanged. The material properties remain unchanged with variable temperature along the cantilever probe body.

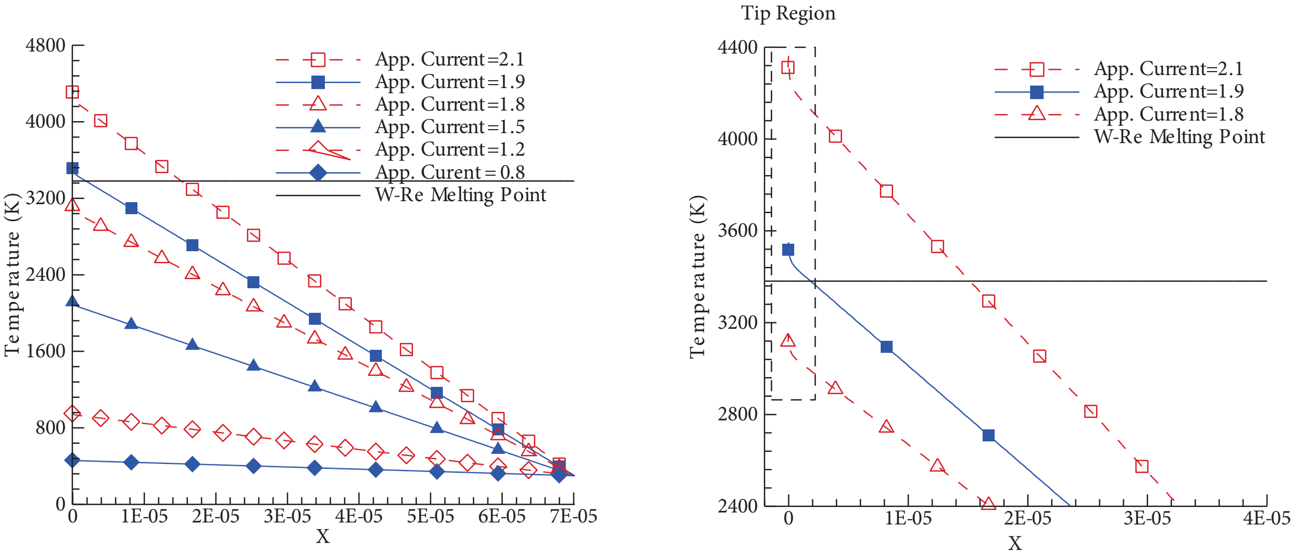
Commercial finite volume analysis (FV) software was used to numerically analyze the temperature distribution in the cantilever probe due to Joule heating. A three-dimensional cantilever wafer probe model is designed in the CAD drawing program and it is used as an input for meshing Figure 11a. The probe body is meshed in the preprocessor program Gambit by using Hex/Wedge type elements with interval size 0.008 as shown in Figure 11b. In the case of meshing, nearly 540,000 elements were used in each analysis. The mesh is exported to the commercial solver along with the physical properties of the cantilever probe material and the initial conditions specified. All cases are solved under transient condition.

In this study, a computational mechanics simulation framework is conducted for the cantilever wafer probe in order to investigate the probe burn phenomenon. The numerical results are computed and the temperature rise is observed along the probe body. Applying the boundary conditions $T|_{x=L}=T_a$ at the base (i.e. representing epoxy wall) and the epoxy wall temperature, T_a, is taken an ambient temperature. Joule heating at the cantilever probe tip is defined according to Eq. (6) for $I_{app.}$ ranging between 0.8 A and 2.1 A for six different cases by using a UDF. The converged numerical results are shown in Figure 12. The effect of the applied current that is generated in the tester on the temperature distribution is investigated. As a comparison, the current carrying capability has reached 1.9 A in the experimental results and between 1.8 and 1.9 A in the numerical results.



(a) (b)

Figure 11. a) Cantilever probe CAD model b) meshed cantilever probe in the case of interval size 0.008.



(a) (b)

Figure 12. Numerical results for different applied current ($I_{app.}$) a) whole probe body temperature distribution is depicted and b) tip region is detailed.

5. Results

In order to compare the performance of mechanical degradation results, experimental set ups are constructed and temperature distribution is computed along the probe body via numerical techniques. In this research concerning the probe tip overdrive (OD) limitation, the initial deflection of OD is applied for each probe diameter at 5-g force as an initial value.

The test procedure is followed step by step and the voltage setting is 5 V for all cases. The results are shown in Figures 9 and 10. The maximum allowable loss of contact force due to current passing through a probe body is 20%, as mentioned before; therefore, $I_{\%20}$ current values are computed from experimental results. The conducted results are $I_{\%20} = 1.9$ A. In the case of the numerical results, the heat conduction equation is numerically solved using finite volume discretization. A comprehensive model that incorporates all the terms was developed and used to characterize variations in temperature as a function of the conducted electrical current (i.e. Joule heating) and applied current is between $I_{app.} = 1.8$ and 1.9 A to melt the probe tip.

Using predictive tools via an experimental and numerical approach to the probe current carrying capacity, the service life of the probe card can be extended and the overall cost of ownership reduced due to lower probe failure rates. This is because the design parameters for the probe tip and the probe geometry can be modified to better fit the requirements of the device application. In experimentation, it is much more difficult to correctly determine the temperature distribution along a probe body. If a proper probe and tip design cannot be created for the specific probe card design requirements, then thermistors can be used in the circuit, assembled on the printed circuit board, to balance and distribute the current load on the probe card and the device under test. Probe burn is expected to happen at the tip section where the maximum temperature is reached. The computation shows higher temperatures towards the probe tip region as a result of Joule heating. The probe burn is also observed at the tip region of cantilever probes in wafer testing. This is thought to be due to very low heat dissipation rates resulting from very small sizes compared to the probe body. Complementary results will be used to improve probe lifetime using more efficient thermal management via flow convection.

Acknowledgment

This research was supported by a Marie Curie International Reintegration Grant within the 7th European Community Framework Program under grant # 271545.

References

[1] International Technology Roadmap for Semiconductors, ITRS 2009 Edition, Test & Test Equipment.

[2] Allison M. Wafer Probe acquires a new importance in testing. Chip Scale Review, May-June 2005. pp. 45-49.

[3] Tunaboylu B, Caughey E. Vertical probe development for copper probing challenges. Semiconductor Wafer Test Workshop, June, 2003.

[4] Kazmi R, Kilicaslan H, Hicklin J, Tunaboylu B. Measuring current carrying capability (CCC) of vertical probes. Semiconductor Wafer Test Workshop, June 2010.

[5] Loh E. Physical analysis of data on fused-open bond wires. IEEE T Compon Hybr 1983; 6: 209-217.

[6] Loh E. Heat transfer of fine-wire fuse. IEEE T Compon Hybr 1984; 7: 264-267.

[7] Mertol A. Estimation of aluminum and gold bond wire fusing current and fusing wire. IEEE T Compon Pack B 1995; 18: 210-214.

[8] Shah M, Rabany A, Campillo JJ, Scharr T, Mares E. Temperature rise and fusing current in wire bonds for high power RF applications. Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM 04 2004. pp. 157-164.

[9] Pitney KE. Ney Contact Manual-Electrical Contacts for Low Energy Uses. Bloomfield, CT, USA: The J. M. Ney Company, 1973.

[10] Holm R. Electrical Contacts: Theory and Applications, 4th ed., Berlin, Germany: Springer Verlag, 2000.

[11] Daniels B. ISMI Probe Council-Current carrying capability measurement standard. Semiconductor Wafer Test Workshop, June 2009.

[12] Lienhard HJ IV, Lienhard HJ V. A Heat Transfer Textbook, 3rd ed., Cambridge, MA, USA: Phlogiston Press, 2004.