Comparison Between Beryllium-Copper and Tungsten High Frequency Air Coplanar Probes

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Abstract—**High frequency air coplanar probes using tungsten tips are now available for silicon wafer probing with aluminum pads. A comparative study of the beryllium-copper and tungsten behavior is presented in terms of contact resistance values, stability and reproducibility. The contact theory is summarized for practical purposes and probe cleaning methods are exposed. Finally, tungsten is demonstrated to be the best material for breaking the aluminum oxide over the pad to enable accurate high frequency probing.**

I. Introduction

On-WAFER high frequency measurement is one of the major activities in microwave and radio frequency domain. HF measurements are performed in order to characterize many kinds of devices (transistors, passive elements, complex circuits ...) on different substrates (GaAs, Si...). New and faster silicon technologies (MOS and BICMOS) are able to play an important role in the high frequency domain. As the size of advanced MOSFET's and BJT's shrinks, very high frequency measurements are required to enable accurate circuit simulation. Accurate measurements are obtained by using efficient calibration methods and de-embedding procedures. In addition, the equipment may have a great influence on result accuracy [1]. Variation of contact resistance is one of the major problems occurring in silicon wafer probing on aluminum (Al) pads. High frequency probing has been conducted for many years on dedicated HF substrates where metallization is more often made of gold. Beryllium-copper probes (also nickel probes) are used intensively and are certainly the best choice. For aluminum pad probing, the situation is very different as the aluminum pad is covered with 50 to 100 Å of hard natural aluminum oxide [2]. For the first time, an HF probe supplier—Cascade Microtech—can provide specific HF probes, using tungsten material, for these kinds of applications in an industrial environment [3], [4].

Tungsten and beryllium-copper material have been used intensively in DC and low frequency probing and tungsten is claimed to be specialized for noncritical applications in terms of contact resistance [5], [6], this is not the case for accurate HF measurements.

In this paper, after introducing the contact theory, the state of art in DC probing is summarized to obtain pertinent information for HF probing and completed by specific measurements. Contact resistance measurement results on the two kinds of probes are presented to indicate the optimum material for HF probing on aluminum pads. Cleaning methods are briefly reviewed and a new practical method is given with its convincing results.

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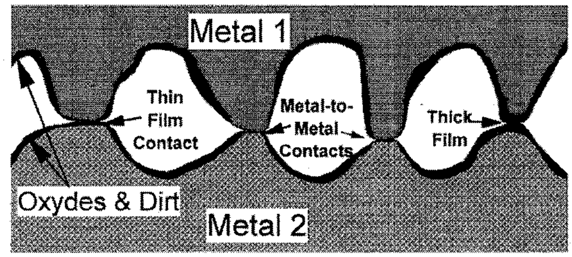

Fig. 1. Contact interface illustration.

II. Contact Theory

The major publication on electrical contact theory has been done by R. Holm in 1967 [7]. Since then, much work has been devoted to this subject as shown by the dedicated international conference so-named "The Holm Conference on Electrical Contacts."

The contact theory starts with the fact that the contact surface is never really flat. As a consequence, the real "mechanical" contact area is much smaller than the apparent contact surface or, in other words, than the tip surface. Second, the metallic materials are more often covered by either oxides, dirt or both. The meeting of the two contact surfaces is illustrated in Fig. 1.

The metal-to-metal peaks elastically and plastically deform until the force on the contact is supported [8]. Then, the apparent contact surface normally remains unchanged and may be described as in Fig. 2.

Not only is the real contact area smaller than the whole apparent contact surface but also some of the real contact areas may be absolutely nonconducting. In fact, these islands may consist of three different regions:

1) Metallic contacts where the current passes through the interface without transition resistance.
2) "Semi-conducting" regions which are thin film covered and have higher resistance than metallic spots.
3) Nonconducting areas where thick insulate films prevent any conduction.

Different models have been developed for predicting the contact resistance [9]–[16]. The less complicated model, which

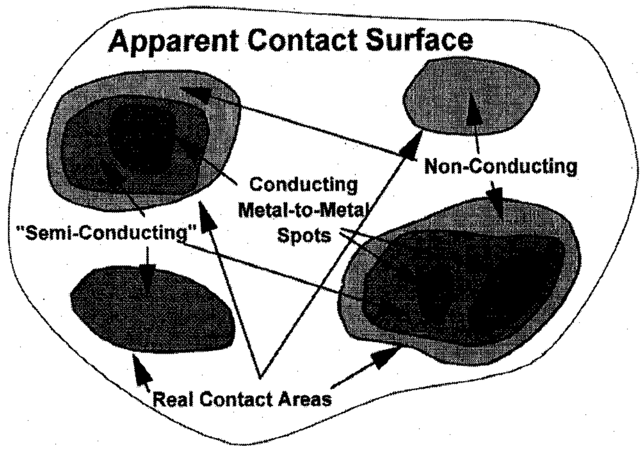

Fig. 2. Contact areas.

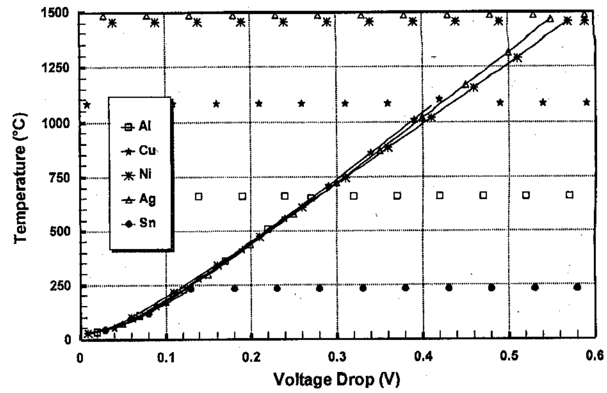

Fig. 3. Spot temperature across the contact interface versus voltage drop.

is very helpful for handy calculation uses the assumption that the contact surface of a metallic spot can be delimited by a circle of average radius a. Then, since the current is forced to flow through the conduction spot, a constriction resistance R_k occurs which can be calculated by [8], [15]

$$R_k = \frac{\rho_1 + \rho_2}{4a} \quad (1)$$

where ρ_1 and ρ_2 are the resistivity of the metal 1 and 2. When metal is covered by thin films (oxides, dirt,...) the contact resistance of the spot R_c becomes

$$R_c = R_k + R_f \quad (2)$$

where R_f is the thin film resistance. Then, the total contact resistance R_{ct} is given by

$$R_{\text{ct}} = \left[\sum_{i=1}^{\text{nb spots}} \frac{1}{R_{\text{ci}}}\right]^{-1}. \quad (3)$$

Assuming only metal-to-metal spots are existing, as should be the case for probing since contact is established with lateral displacement, the average radius of the equivalent spot contact may be estimated from the relation (1) as

$$a = \frac{\rho_1 + \rho_2}{4R_{\text{ct}}}. \quad (4)$$

At this time, it is important to note that, since the real contact area is generally dependent upon the contact force, the surface profile and the hardness of the materials and not upon the apparent surface area [8], the contact resistance is not really and directly related to the apparent contact surface.

If the contact interface is assumed to contain n conducting points of equal size [17], the average radius of one spot would be given by

$$a = \frac{\rho_1 + \rho_2}{4nR_{\text{ct}}} \quad (5)$$

and then, the current density through one spot would be expressed as

$$J = \frac{I}{nS} = \frac{I(4nR_{\text{ct}})^2}{n\pi(\rho_1 + \rho_2)^2} = \frac{16nU^2}{\pi(\rho_1 + \rho_2)^2 I} \quad (6)$$

where S is the area of the contact spot (πa^2), I the whole current through the contact and U the voltage drop. In these conditions and for the case of probing aluminum with tungsten needles ($R_{\text{ct}} = 250$ mΩ), with a current of 25 mA, the lower current density, which is obtained for $n = 1$, would reach $1.11 * 10^8$ A/cm^2. Then, electromigration of aluminum can occur even at such a low current. This problem (or oxidation process) has ever since been suspected during probing for electromigration purpose with apparent lower current density ($1.5 * 10^6$ A/cm^2) [18].

With such high current densities, the local spot temperature T_s may become important. This temperature, for a circular spot in the interface between conductors of the same metal can be expressed as [17]

$$T_s = T_b + \sqrt{\frac{U^2}{4\alpha\rho\lambda} + \frac{1}{\alpha^2}} - \frac{1}{\alpha} \quad (7)$$

where T_b is the bulk temperature (generally the room temperature), α and ρ are the temperature coefficient of resistivity and the resistivity at bulk temperature, and λ is the thermal conductivity. Fig. 3 presents, for different metals, the spot temperature versus the voltage drop at room temperature. The curves stops at the melting temperature (horizontally placed symbols) of each metal (material data from [19]).

Assuming that the tungsten- or BeCu-to-aluminum spot temperature may be described by the relation 7, the aluminum melting temperature is reached when the voltage drop is about 250 mV or, in other words, when probing with current of 1 A through the contact resistance of 250 mΩ. This effect has been experimentally, but involuntary, verified for BeCu-to-aluminum connection when serial resistance with the metallic spots suddenly decreased and the probing current reached 1A. The result was the soldering of one tip on the aluminum pad.

Many studies have been conducted to identify processes affecting the contact connection and, according to M. Braunovic [19], these processes may be oxidation, stress relaxation, differential thermal expansion, galvanic corrosion, formation of intermetallic compounds, and fretting. The last point seems not applicable for probing operation since movement normally occurs only during the contact establishment. Nevertheless, for

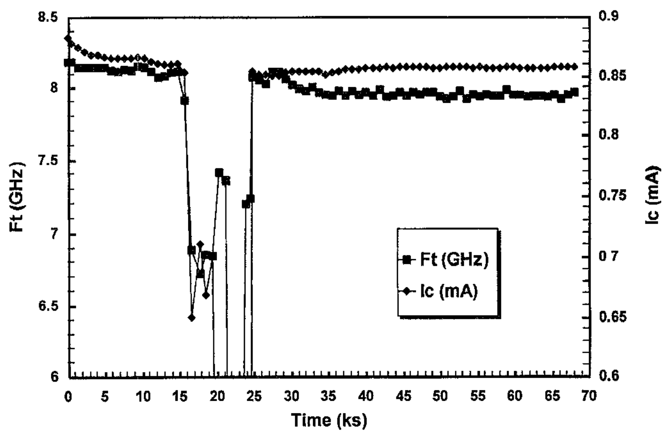

Fig. 4. Measurement reproducibility versus time of contact (Example of contact loss).

automatic probers, vibrations were sometimes observed due to the motorization control loops. In this case, the contact resistance is degraded due to the fretting effect which allows the formation of intermetallic compounds, the oxide building up and finally the creation of thick insulating films. It was demonstrated that high contact pressures reduce dramatically the effect of fretting [20]. Unfortunately, the shape of HF probes is guided by propagation considerations [21] which are in contradiction with high contact pressures due to the low angle between the tips and the pad plane.

Probing activities are probably not affected by the previous other mechanisms which should not occur in a normal environment with short time contact, provided low currents are used. Still, the oxidation has to be carefully treated. Indeed, thin films of aluminum oxide are instantly created in normal environment. When the contact is done with clean tips, these very hard films, but also very thin, are easily broken provided the pad aluminum alloy is soft enough. Even if it is not the case, the conduction can take place due to the tunnel effect. On the other hand, after probing, the tips may be covered by thin aluminum films which will naturally oxidize and these new oxide films are difficult to break as they cover hard material. Furthermore, successive aluminum deposition and oxide film creation may insulate the tip surface. It may also be noted that tungsten and BeCu materials are also covered by their own oxide films.

Oxidation can also affect the contact resistance during probing due either to low force probing which may allow the separation of the two contact surfaces, or to the existence of contaminants at the aluminum pad surface [22]. These effects were observed when probing with very low current density, very short time of current circulation but with long time of mechanical contact. Fig. 4 exhibits, for a silicon bipolar transistor, the variation with time of the current collector and of the F_t parameter extracted from the S-parameter measurements [23]. After about four hours, during which the collector current was seen to be slowly and continually decreasing without major effect on F_t, the electrical contact disappeared. After full contact loss, a very soft vibration was sufficient to come back to the conduction for more than eleven hours, but showed variation on the F_t parameter. This indicates a dual effect of the contact resistance. First, for active devices, the DC biases are affected and consequently the AC parameters can change. Second, for active or passive devices, the contact impedances, which can be modeled by a resistor in series with an inductor [23], [24] (typically about 1 Ω and 40 pH at 10 GHz [23]), can affect directly the S-parameters depending upon the device under test. It must be noted that the value of the contact impedance is not of prime importance since it can be corrected by a specific de-embedding step, provided it remains stable during the time of probing and from one contact to the next.

In order to indicate all the major effects of the contact resistance on the measurement, it is important to note that probe contact will introduce additional noise [25] and that its effect analysis has to take account of the real behavior of the contact interface [26].

III. DC AND LOW FREQUENCY PROBING

Static and low frequency measurements at wafer level have been conducted for many years on silicon wafers with aluminum pads. Beryllium copper (BeCu), tungsten (W) and palladium (Pd) are the most widely used materials for these kinds of probes. Tungsten needles have been used for all noncritical applications where contact resistance values have no significant effect, whilst BeCu tips have been used for high speed and high power applications because they offer the lowest probe contact resistance. In addition, the contact resistance of tungsten probes degrades, that is increases, with use. These facts seem to suggest that tungsten is unsuitable for HF probing.

In fact, tungsten offers several advantages over BeCu. First, tungsten is the best material for breaking the aluminum oxide over the probe pad of the wafer. It exhibits an excellent fatigue resistance and produces very consistent contact pressure with repeated use. Moreover, its hardness provides long probe life. The contact resistance of clean tungsten needle is typically about 250 mΩ. Unfortunately, this value may increase and may exceed 5 Ω after several opérations [5], [6] (50 to 500 Ω has been often observed [6]). According to M. Schell and J. Sanders [5], this is due to the constitution of the tungsten needles, which are formed by compressing strands of tungsten together. They pick up aluminum and aluminum oxide from the probe pad, and aluminum oxide builds up on the probe tips. As a result, the contact resistance gradually increases.

On the other hand, beryllium copper contact resistance is typically about 200 mΩ and remains stable thanks to a kind of "self cleaning action."

The most important parameter for probing is the contact pressure as this determines how well the electrical contact is established between probe and aluminum pad and how well the probe tip will punch through the aluminum oxide. Obviously, the contact pressure depends on the tip area and the tip force, which is related to the overdrive, the probe shape and the elasticity of the probe material. Contact pressure is much more important for tungsten probes, when considered against similar BeCu probes, due to the stiffness of tungsten being three times greater than that of BeCu.

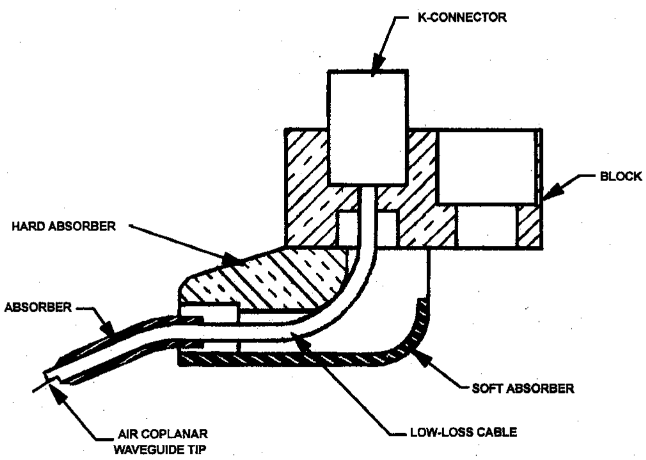

Fig. 5. Cross section of the ACP probe (from [3]).

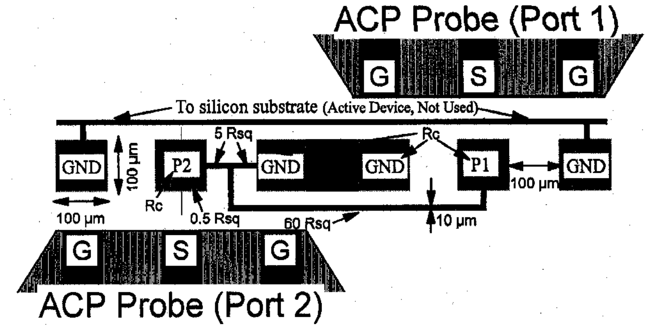

Fig. 6. Pattern used for contact resistance measurements.

IV. Specificity of High Frequency Probing

A cross section of a HF air coplanar probe is given in Fig. 5. The tungsten and BeCu probes are made of the same body and only the air coplanar waveguide tips are replaced with the appropriate material. This material is gold plated to reduce the conductor loss (effects upon contact resistance occur only for the first few probing operations, due to tip wear).

The main difference between the HF and DC probes concerns the tungsten material which, in HF probes, is not obtained by compressing strands of tungsten together. Consequently, evolution of contact resistance should remain of the same order for BeCu and tungsten.

V. Experimental Equipment and Set-up

The experimental set-up consists of a full automatic cassette-to-cassette probe station for 4″ to 8″ wafers. The prober (APM90A from Tokyo Seimitsu Co.) is able to measure and check the X, Y and Z positions of each tip. It automatically corrects the wafer thickness variation from wafer to wafer and from die to die on the same wafer. For each measurement, the overdrive is the difference between the measured height of the wafer surface (capacitance measurements) and the measured height of the tips (optical measurements—camera focus). It cannot correspond to an overdrive calculated from a height reference obtained by DC electrical measurements.

The station is located in a class 1000 clean room and the temperature is regulated at 21.5°C ± 0.5°C.

A DC bias unit (HP-4142) is used for DC probe card measurements as well as for HF probe measurements. In the case of DC probe cards the SMU's (i.e., the outputs of the DC source) are connected to a commutation matrix (HP-4085M) via triaxial cables. As a result, measured contact resistances contain the contact resistance of the matrix relays and of the interface matrix to card support and card support to probe card. For HF probes the triaxial cables plug into the DC bias tees. The measured contact resistances contain the series resistance of the bias tees, the HF coaxial cables and the HF SMA connectors.

After adjusting the HF probes, thanks to the micro-positioners (X, Y, Z, and θ adjustments), the angle difference between the HF probe plane and the surface of wafer is less than 3 degrees and the difference in tip height is less than 10 μm.

In addition, a HP-8510C network analyzer is normally used for HF measurements, but it was only used to check the correlation between DC and HF behavior of the contact resistances and for the F_t determination presented in Fig. 4 of the Section II.

DC measurements are conducted on one BeCu and one W DC probe cards and on one couple of BeCu and one couple of W HF ACP probes. For each measurement, the tips are placed on a new structure which has never been probed.

The measurements are performed using the available pattern on our silicon wafers depicted in Fig. 6. It corresponds to a "SHORT" dummy structure used for de-embedding purposes. This pattern was designed for production monitoring with high frequency measurements since they can be located in the scribe lanes of production wafers.

DC probe card measurements use the two pads (GND-GND) connected together by the widest metal line. In these conditions the resistance of the line can be neglected.

In order to characterize the contact resistance of the two HF probes together, the GSG probes are placed as illustrated in Fig. 6. The opposite port is forced to zero voltage for this test. Unfortunately, for HF ACP probes, the lines connecting the two probes cannot be neglected. Since there is a difference between the resistance measured at port 1 (R_{P1}) and that measured at port 2 (R_{P2}), assuming the equality of all contact resistances, the value of contact resistance (R_c) may be extracted from global measurement by solving the linear equations

$$R_{P1} = R_c + 60.5R_{\rm sq} + (5.5R_{\rm sq} + R_c)/2 \tag{8}$$

$$R_{P2} = R_c + 5.5R_{\rm sq} + 0.87(5.5R_{\rm sq} + R_c) \tag{9}$$

where $R_{\rm sq}$ is the square resistance of the aluminum metallization. (The 0.87 factor in Eq. 9 comes from the equation linearization: $(5.5R_{\rm sq} + R_c)//(60.5R_{\rm sq} + R_c)$.

VI. DC Probe Card Measurements

Fig. 7 presents the typical variation of the contact resistance with time using clean BeCu and tungsten probe cards on aluminum pads for long time probing, is quite stable. However,

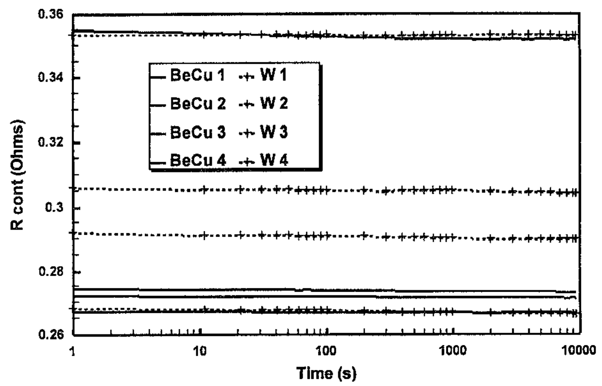

Fig. 7. Contact resistance of BeCu and W DC probe cards versus time.

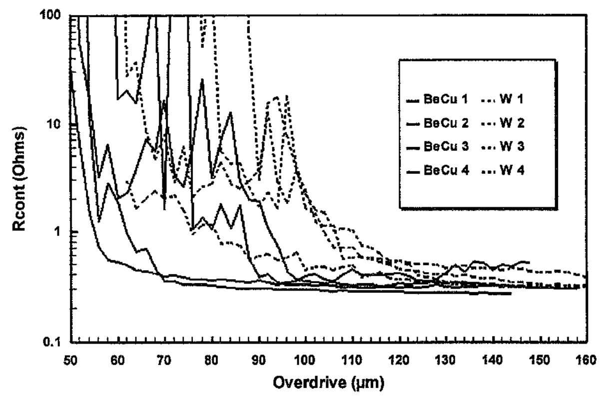

Fig. 8. Contact resistance of BeCu and W DC probe cards versus overdrive. (Measurements on the same structure with continual increasing of the overdrive.)

high values of contact resistance (1 to 15 Ohms), linked to strong unstable behavior with time, were found using BeCu probe cards due to either dirt or old probe cards, or even with new clean probe cards. Similar results, concerning tungsten probe cards, have been presented in previous publications [27].

The variation of the contact resistance with overdrive is presented in Fig. 8. At low overdrive, the resistance is highly unstable due to low penetration of the tips into the dirt and oxide layers above the pad [28].

VII. HF Probe Measurements

The contact resistance of beryllium copper and tungsten probes on aluminum pads versus number of times probed is given in Fig. 9. Slight differences can be observed in contact resistance: 0.25 $\Omega\pm$ 8% for BeCu probes and 0.29 $\Omega\pm$ 10% for W probes. The sheet square resistance (R_{sq}) of aluminum metallization is also reported to indicate the quality of our extraction procedure. Measurement of this parameter using Kelvin probes indicates 64 mΩ for this technology. The overdrive was of 150 μm for BeCu probes and 100 μm for tungsten probes. These values correspond to the optimum overdrive in order to obtain stable contact resistance for a long time contact. It was observed that BeCu probes do not have enough pressure to punch through the aluminum oxide and slide over the pad surface and consequently they required higher overdrives.

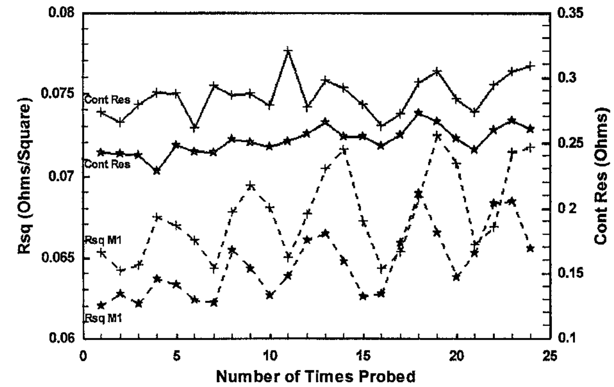

Fig. 9. Contact resistance of ACP probes ($*$BeCu, $+$W) versus number of times probed: contact resistance of BeCu ACP probes: 0.25 $\Omega\pm$ 8%@ overdrive = 150 μm; contact resistance of W ACP probes: 0.29 $\Omega\pm$ 10%@ overdrive = 100 μm.

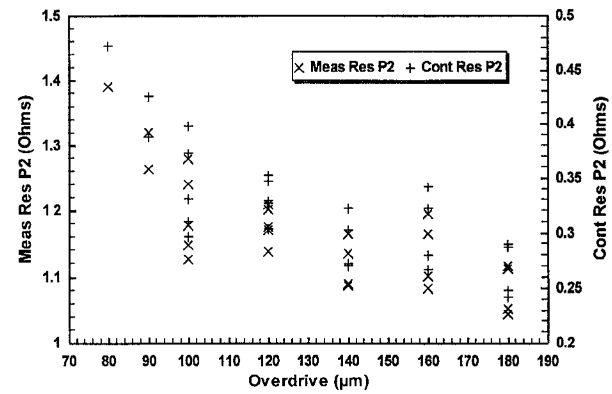

Fig. 10. Contact resistance of one pair of BeCu ACP probes versus overdrive.

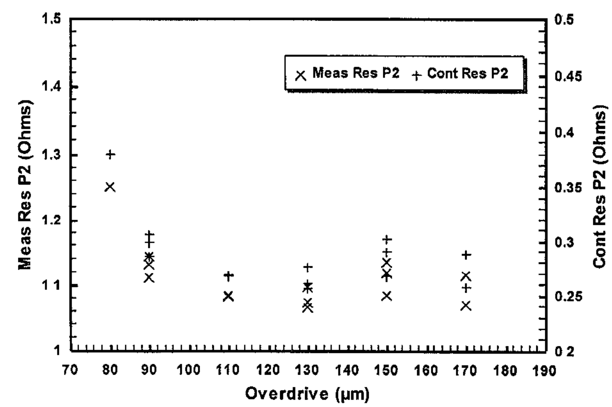

Fig. 11. Contact resistance of one pair of W ACP probes versus overdrive.

Figs. 10 and 11 present the contact resistance (and also the total resistance at port 2) versus the overdrive for beryllium copper and tungsten probes, respectively. For these measurements, as can be seen in Fig. 8 at low overdrive, the assumption of equality of all contact resistances is no longer valid [28]. The difference between the currently measured resistance and the minimum value at port 2 is corrected to provide an evaluation of the contact resistance.

The increase of the contact resistance at high overdrive is attributed to the fact that the tip surface, which contacts the

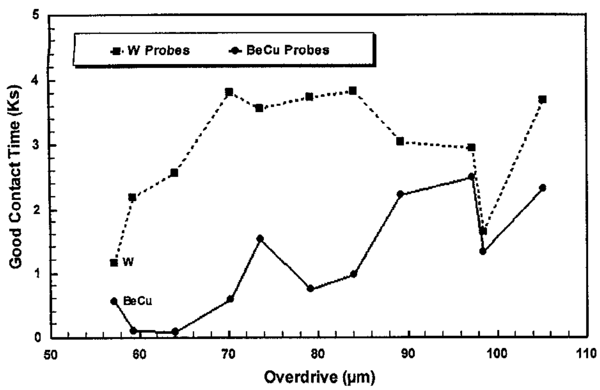

Fig. 12. Time of good probing for ACP probes.

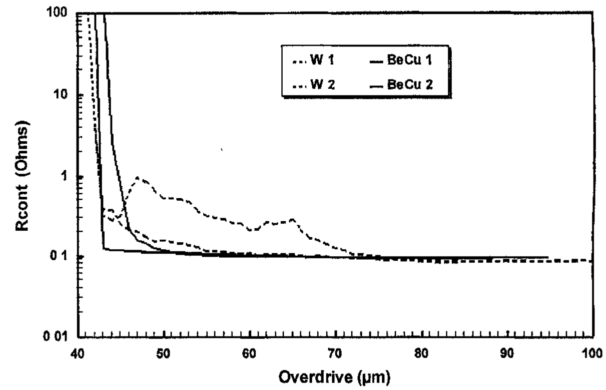

Fig. 13. Contact resistance of ACP probes on gold metallization versus overdrive. (Measurements on the same structure with continual increasing of the overdrive.)

aluminum pad, is the place where aluminum oxide builds up due to previous probing. BeCu and tungsten probes exhibit similar behavior with overdrive. The small difference in favor of tungsten probes (W: 0.3 Ω@ 110 μm; BeCu: 0.35 Ω@ 140 μm) was found not to be reproducible when making many measurements. Finally, overdrives of 80–90 μm are required to be beyond the "knee" of the curve and contact resistances reach 0.3 Ω for BeCu as well as for tungsten probes. Differences in successive measurements are due to imperfect cleaning of the probes.

Measurement were also conducted on aluminum covered wafers for which the aluminum alloy was largely softer than for standard metallizations. The contact resistance was found to be about 100 mΩ for BeCu probes and about 150 mΩ for tungsten probes, at 80 μm of overdrive. This fact indicates how important the hardness of the aluminum is, for breaking the aluminum oxide. Nevertheless, these last results are not a criterion for selecting the probe material since this configuration will never correspond to our real probing situation.

The next point concerns the ability of the probes to remain stable with the time of probing. For our standard characterization the maximum time of probing is generally about 45 minutes (2700 seconds) and these tests were stopped after about one hour of probing. The criterion of good probing time has been defined as the time while the total resistance variation remains less than 0.01 Ω (i.e., less than about 2% of the whole contact resistance value). Averaging of ten measurements at each overdrive indicates a better behavior of the tungsten probes (Fig. 12). It is important to note that these results were obtained using the semi-hard cleaning method which will be presented in the next section.

Finally, the contact resistance of the two probes on gold pads is presented in Fig. 13 to indicate the difficulty of probing on our aluminum pads, when comparing with Figs. 10 and 11.

VIII. Probe Cleaning Methods

The cleaning methods may be classified as very soft, semi-hard, and hard methods. The soft methods may consist in blowing air on the probes, from the body to the tips. Other methods involve the use of a fine camel hair brush or a foam-tipped swab with isopropyl alcohol (IPA). These methods have been found not efficient when probing on aluminum pads.

For DC probe cards a three-minute soak in TCE (trichloroethane) can be used [29], but this method, or the use of acetone, is not recommended by the HF probe manufacturer.

Semi-hard methods may be ultrasonic cleaning with soaking (TCE) or chemical cleaning with a 20% solution of potassium hydroxide [29] or a solution of hydrofluoric acid [30]. Nevertheless, the time of soaking has to be carefully controlled to prevent attacks on the probe materials. Furthermore, the use of these products may be very dangerous without specific precautions.

Sandblasting [29] is a satisfactory hard method, but it requires specific and expensive equipment.

Abrasive methods using either alumina ceramic [29] (available on our prober) or sand papers [30] are certainly efficient but they may induce a high wear of the tips. Consequently they have to be used very carefully. That may be done by moving the probes on the ceramic surface of the calibration substrate while gently increasing the overdrive. Results are quite good, but this method requires calibration substrate loading which is very time-consuming.

In order to obtain sufficiently small contact resistance, a semi-hard method was used which consists of increasing by 10 to 20 μm the overdrive each time before breaking the contact. Oxides and other dirt clinging on the tips are shaken off and a large part of them are held back on to the pads. That increases the self cleaning action and is especially efficient with BeCu probes.

With this method, not only the reproducibility was improved (see Figs. 14 to 15, for BeCu probes), but also the time of good probing (5 times longer).

IX. Conclusion

The major processes predicted by the contact theory have been discussed in order to indicate how they can affect the contact quality, and an experimental study of beryllium copper and tungsten probes designed for high frequency measurements has been performed on the range of DC electrical contact quality.

Tungsten material has been found to be the best tip material for HF probing wafers with aluminum pads covered with aluminum oxide. The optimal material for the main characteristics

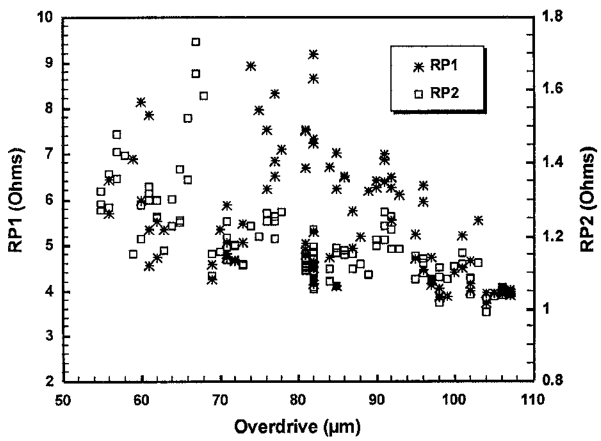

Fig. 14. Measured resistance (port 1 and 2) using BeCu ACP probes versus overdrive without semi-hard cleaning method.

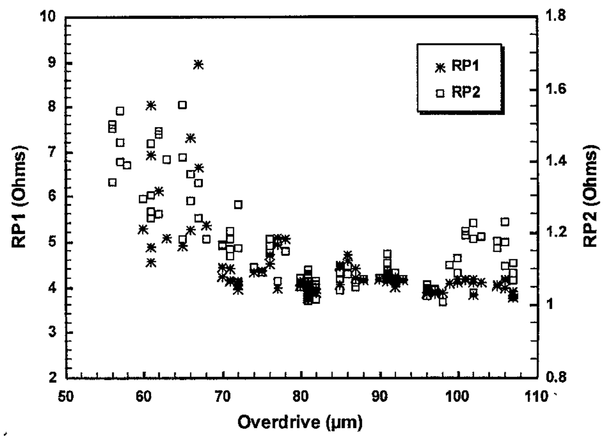

Fig. 15. Measured resistance (port 1 and 2) using BeCu ACP probes versus overdrive with semi-hard cleaning method.

TABLE I
OPTIMAL MATERIAL FOR HF ACP PROBES VERSUS PROBING CHARACTERISTICS

Characteristics	Optimal material	Comments
Low contact resistance (R_c)	BeCu	Weak advantage (0.25 Ω against 0.29 Ω) {Fig 9} Can be corrected with de-embedding step
Reproducibility of R_c	BeCu	Weak advantage (8% against 10%) {Fig 9}
Overdrive (minimum R_c)	W	Weak advantage {Fig 10 and 11}
Overdrive for R_c stability	W	Effect on life time
Cleaning period	BeCu	Weak effect on life time
Life time	W	Decrease the probing costs
Stability during probing	W	Strong advantage (1 hour against 15 mn) {Fig 12} Cannot be corrected

in wafer probing are summarized in Table I with specific comments for HF probing.

The contact resistance of tungsten probes is not much higher than beryllium copper and lower overdrives are sufficient for tungsten probes. The lifetime of beryllium copper probes, which is shorter than that of tungsten probes, will be reduced by the use of the large overdrive to make good contact and by periodic cleaning of the tips where aluminum oxide builds up.

Long time probing can only be achieved with tungsten probes which offer sufficient contact pressure, but contact resistance evolution with repeated use seems to be a little more important than for BeCu probes and a shorter period between cleaning may be required.

Improvements in contact quality, and as a result in DC and HF measurements, should be obtained using together appropriate periodical cleaning procedures, as depicted in this paper, and specific aluminum pads which may consist, for the last level of metallization, of pure aluminum or a particular alloy in order to obtain a very soft layer under the aluminum oxide.

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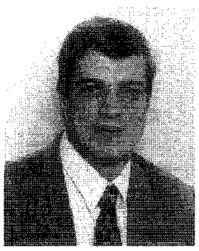

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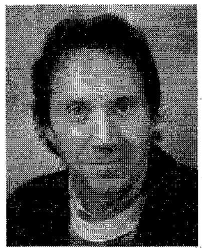

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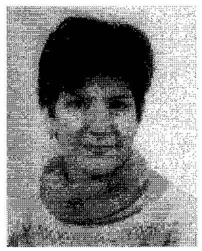

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