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Forensic Engineering Analysis of Test Equipment Manufacturing Capability in a Business Purchase Dispute

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Abstract

A privately owned semiconductor test equipment company was sold by its U.S. domestic owners (seller) to a purchaser having an overseas manufacturing location (buyer). The sale was to take place in several stages. The buyer asserted that when the agreement was made he was unaware that the seller's flagship product was being rejected by customers for not meeting specifications. When this came to light, the buyer refused to continue with the second and subsequent stages of purchase. The seller then sued the buyer for not complying with the agreement, and the buyer counter-sued for fraudulent deception. The author was retained by the buyer's attorney to review specification documents regarding the product, due diligence reports, and e-mail chains regarding product quality, field returns, and repairs.

Keywords

Forensic engineering, semiconductor, semiconductor wafer, integrated circuit, IC, IC test, automatic test equipment, ATE, wafer, chip, die, wafer test, wafer probe, probe-card, vertical probe

Introduction

This case relates to equipment used for testing an integrated circuit (IC) during its manufacture while it is still part of a semiconductor wafer. As background, an individual, bare, unconnected, integrated circuit is called a die (plural, dice). Each die is separately tested while still part of the wafer. A wafer-probe gets its name from the procedure of lowering needle-like metal probes onto the die where they pierce the surface of bump-like solder connection pads on the die to make electrical contact between the tester and circuitry on the die. The collection of probes and associated hardware is referred to as a " probe-card." A custom probe-card is designed for each IC product. Custom software controls general-purpose automated test equipment (ATE) for testing each IC product.

The very first wafer-probe test validates contact — electrical continuity between the tester and the die. Following the contact test, typically thousands of additional tests are performed on each die. When final testing is completed, the probes are lifted, and the wafer is shifted to bring the next die under the probes. The sequence of probe/test/shift is repeated until each die on the wafer has been tested.

After wafer-probe, the wafer is singulated (cut up) into individual dice. Those that failed wafer-probe are discarded; those that passed are mounted into packages. A finished IC package includes the die and connecting wires from the die to pins on the outside of the package.

The seller's company designed, manufactured, and sold probe-cards to semiconductor manufacturing companies. Early in its history, the seller's product was uniquely innovative and captured the lion's share of the probe-card market. After its leadership position was lost, financial difficulties ensued. As a result, the seller sold the company to the buyer. For multiple reasons, the buyer decided not to finish the purchase after the first stage of a multi-stage transfer. The two parties were not able to settle the dispute; therefore, the seller sued the buyer to force completion of the purchase.

Overview of Integrated Circuit Design, Fabrication, Testing, and Packaging

Integrated circuits contain highly concentrated

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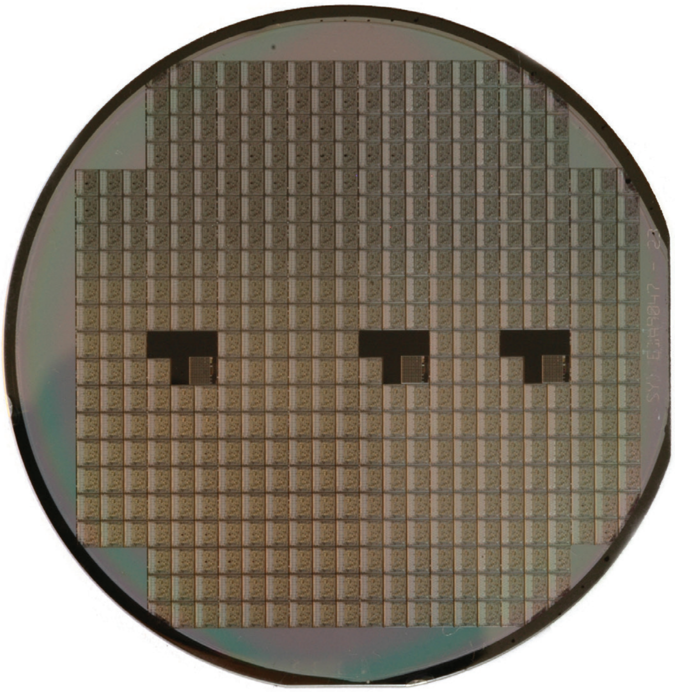

Figure 1
A semiconductor wafer with fabricated IC dice[4].

electronic equivalents of discrete components, such as resistors, transistors, capacitors, and inductors.

Figure 1 shows a finished semiconductor wafer with an array of IC dice visible on its surface. A diameter of 300mm is a typical wafer size[1]. Typical die sizes can range from about 2 by 2mm to 20 by 20mm^2. A typical package size for the types of ICs in this case[3] is about 40mm^2.

A critical part of the design process is to choose the physical location of IC input and output (I/O) pads on the surface of the die. Early integrated circuits placed I/O pads on the perimeter of each die. As more circuitry and I/O were added to ICs, the dimensions of the chip were governed by the perimeter length, which, in turn,

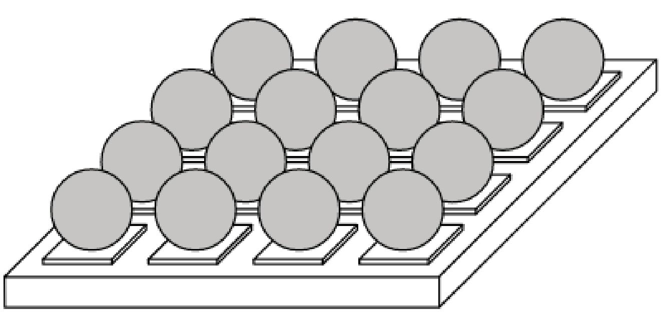

Figure 2
Illustration of a solder bump matrix[7].

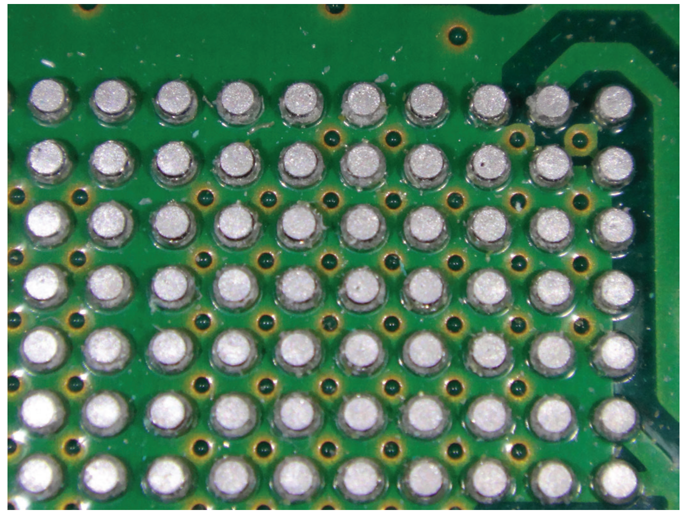

Figure 3
Close-up of solder bumps[8].

was governed by the number of I/O. Valuable area on the inside of the die was wasted. By the early 1990s, the ball grid array packaging technique made it possible to design a two-dimensional array of hemispherical connecting pads distributed across the surface of the die. Ball grid array (BGA) I/O enabled the number of connecting pads to increase from hundreds to thousands. **Figure 2** illustrates BGA solder bumps. **Figure 3** shows BGA solder bump connectors[5]. In contrast, **Figure 4** shows an IC with all bond pads on its perimeter[6].

Figure 5 is an overhead photograph of a probe-card used for testing dice with peripheral bonding pads. This probe-card is typically about 6 inches in diameter. So-named cantilever probes extend from the perimeter of the empty square area in the center to a circular support ring where they attach to the copper-color wires connecting to printed circuit board traces. The PCB traces extend

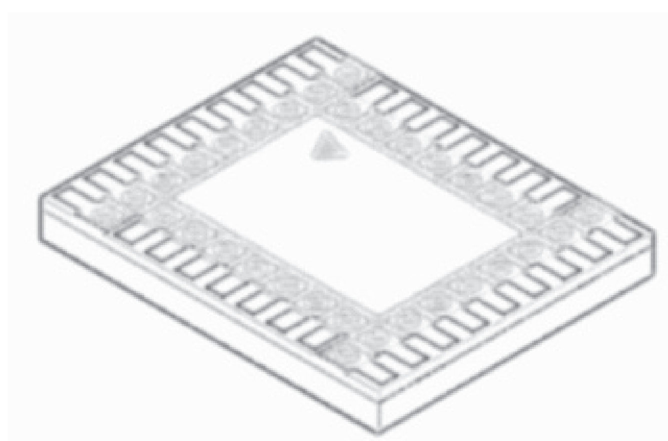

Figure 4
IC die with peripheral bonding pads[9].

Figure 5
Probe-card with cantilever probes for an IC with perimeter bond pads[10].

out to the circular ring of connecting pins that connect to the ATE drive/receive pins. The circular array of circular holes is for fasteners.

Figure 6 is a side-view diagram of a cantilever probe-card. It is the springy characteristic of bending the probes (one is encircled) that allows a controlled force and good electrical connectivity between the probe tip and the bond pad on the die.

In action, these probe elements "touch down" on the probe-pads of each die on the silicon wafer to test the die. The ATE applies voltage to the power supply pads to power up the chip. The ground pads on the chip are connected to a controlled zero-volt reference. The ATE sends test signals through the probe elements to the signal-input bond pads to stimulate the IC. The IC's response signals are conducted back through the output bond pads, through the probes, and ultimately back to the tester. The output signal detected by the tester is compared to what is expected to determine if a given test passes or fails. If all tests pass, the IC is judged to be "good." If any test fails, the IC is judged to be "bad."

Specifics of the Business Dispute

According to discovery documents, during a business downturn (when the seller was in research and development mode), the decision was made to reduce the workforce. Internal memos and emails describe the resulting malaise that spread to core design team members. Certain key team members decided to retire or otherwise leave the company (or the industry as a whole). Despite the pressure on the engineers who stayed to complete the next-generation flagship product on time, the new product line ended up late to market.

Discovery documents showed that the new product received mixed reviews from initial customers. Customer feedback was that it proved satisfactory for testing the existing generation of customer ICs. But, as far as performance went, it did not make the desired leapfrog into the next technology. Large-volume IC manufacturers were demanding this performance.

Multiple discovery documents revealed that the seller's latest generation probe-cards did not have adequate positional stability over time, temperature, and repeated usage. Not all the probes were reliably contacting all the solder bumps. After testing some number of dice on some number of wafers, contact tests would begin to fail

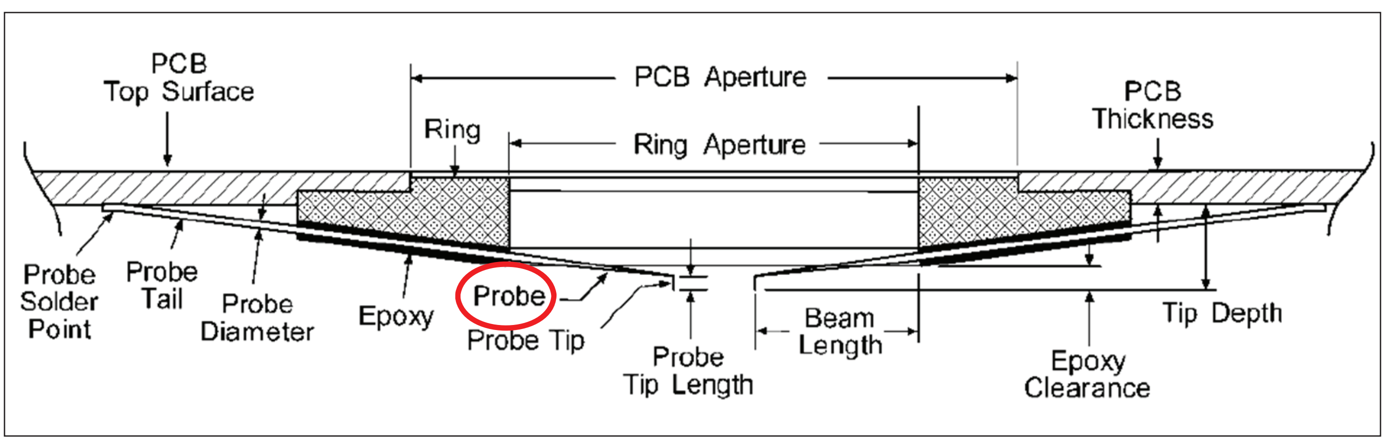

Figure 6
Cantilever probe-card, side view diagram[11]. *Diagram Copyright (C) Tektronix. Reprinted with permission. All Rights Reserved.*

more frequently. Testing ICs at 125°C was required by the seller's customers for certain military and consumer products. High-temperature testing resulted in contact failures occurring more frequently and after probing a smaller number of dice successfully.

A competing probe-card vendor's design team was able to solve the technology challenges for its new generation of probe-cards, and successfully shut the seller out of the market. The revenue increase expected from the new product line did not appear. Discovery documents included exchanges internal to the seller's executives leading up to the decision to sell the business.

A willing buyer was found overseas — a company that was experienced in IC testing products and wished to expand into a line of wafer probing equipment, including vertical probe-cards. The transaction was to occur in three stages.

The first stage began and ended with a down payment of $3 million. Upon this stage, the new company name was announced, and manufacturing continued in the seller's existing probe-card foundries with few personnel changes. Beyond the down payment, the buyer agreed to pay royalties to the seller for four years.

The second stage involved three milestones. A total of $2 million would be payable at their completion.

1. Seller's flagship probe-card product line had to be accepted by a certain well-known IC manufacturer (Customer A) for production-testing of its high-speed video processor IC. It had 8,000 solder-bump bond pads on its die. In addition, Customer A required that each die be tested at two temperatures – "ambient" and 125°C.

This first milestone was negotiated to include the words "or equivalent" for the Customer A IC — that is, if the seller could not convince Customer A to purchase its probe-cards to test its video processing chip, then the seller could alternately meet the milestone by selling the probe-card to some other IC manufacturer (Customer B) for testing an "equivalent" IC. However, the definition of "equivalent" was not stipulated in the sales agreement.

2. The second stage 2 milestone was for the seller to construct an assembly line at the buyer's overseas factory for fabricating older-generation probe-cards that were still being sold to IC manufacturers. Probe-card products manufactured on this new assembly line were required to pass all manufacturing tests and be accepted by customers for production testing of their IC products.

3. A final stage-2 milestone was for the seller to send its manufacturing technicians to the buyer's site to train them to take over the jobs they would eventually lose.

The third stage required the seller to construct an assembly line for the flagship probe-card product at the buyer's factory, and train the buyer's technicians in operating and maintaining that line. It required that the probe-cards pass all internal tests and be accepted by Customer A (or alternatively, Customer B) for IC production testing. A total of $1 million was to be paid at the completion of the third stage. Royalty payments from the buyer to the seller, based on total probe-card sales, were to continue until four years from the initial agreement date.

The Timeline, Dispute, and Ultimate Resolution

The buyer only had access to the day-to-day accounting and sales data for the seller after the agreement was signed, at which point the buyer realized that something was wrong. Communications between the seller and customers, including communications between the seller and Customer A that were unfavorable, had been withheld from the buyer during the pre-sale due-diligence period. The buyer now realized that customers were dissatisfied with the seller's latest product. Customers were returning latest generation probe-cards for repair or replacement in higher-than-expected numbers because the probes were not able to successfully test known good IC dice.

Considering each milestone of the second stage:

1. Customer A, the IC manufacturer of the high-speed video processors, did not accept the probe-card after many attempts to debug and redesign the units shipped to them.

At ambient temperature, Customer A was able to test all dice on one wafer. Too soon thereafter, spurious connectivity failures began to occur. A probe-cleaning procedure that normally was executed once per shift had to be executed after testing each wafer. Probe-cleaning (like knife sharpening) removes material from each probe tip, which are only 75 microns wide to begin with. Thus, each probe would have a shorter useful lifetime, adding to the cost of ownership. A second problem was that when testing at 125°C, the probes were not making reliably good contact with all the solder-bump bond pads. Customer A canceled all orders, and began purchasing its probe-cards from a competing vendor for testing its video processor IC.

Upon receiving this news, the seller proposed to the buyer that a different probe-card of its latest product line fulfilled the "or equivalent" wording of the milestone. This probe-card had been accepted by a different manufacturer (Customer B) for testing a different IC. The equivalence, or not, of these ICs became a matter of contention.

2. The seller had agreed to construct the prior-generation assembly line on the buyer's factory floor as a stage 2 milestone.

The seller's documentation was incomplete. E-mails turned over as part of the discovery process showed that the seller's employees searched through electronic documentation and hard-copy paper filing cabinets, but were not able to compile a complete fabrication document package. E-mail trails indicated that during the debug phase of development, ad-hoc changes to the fabrication procedure would be made by key technicians and were not recorded. The fabrication procedures were carried out by the designers and sometimes communicated verbally, if at all, to other technicians.

According to emails and return-documents from the buyer's customers, the probe-cards produced at the buyer's factory were of inconsistent quality and inferior to those produced at the seller's home factory. The conclusion was that the overseas assembly line was not producing probe-cards that could be sold to existing customers.

3. This same installation and production team was tasked with training the buyer's technicians to build, maintain, and operate similar production lines on their own. These trainers understood that they were training the people who would take over their jobs.

Language and cultural barriers impeded communication between the seller's trainers and buyer's employees (students). The incompleteness of fabrication documents added to the difficulty.

The buyer decided to call off the purchase, claiming that none of the three second-stage milestones had been met — that is:

- Customer A did not accept the probe-card. The buyer claimed that Customer B's product was not equivalent to that of Customer A's.
- Probe-cards produced at the buyer's site on the assembly line set up by the seller's installation team were rejected by existing customers.
- The seller's team was not able to train the buyer's technicians to operate (or duplicate) the assembly line at the buyer's factory.

The buyer intended to completely divest itself of any claim to ownership of the seller's company. The buyer did not ask for the return of the $3 million, but did refuse to make the remaining two payments and continue any royalty payments. The seller demanded that the transfer process continue to the third stage. The seller intended to continue to address the buyer's concerns with the second stage. The seller claimed:

- The IC for which the latest generation probe-card had been accepted for testing by Customer B was equivalent to the video processor IC of Customer A.
- The failure of the newly built assembly line was due to the incompetence of the buyer's workers.
- The training given by the team should have been sufficient for a reasonably competent technician.

Negotiations broke down. The seller brought suit against the buyer to pay for stage 2, to allow procedure to stage 3, and for the buyer to continue paying royalties. The buyer counter-sued for misrepresentation and fraud. The buyer's attorney retained the author through an expert witness agency. The author was asked to opine on:

1. The claimed equivalence of the two ICs.
2. The necessity for documentation.
3. The necessity for training.

Claimed Equivalence of the Two ICs

Since the agreement between buyer and seller did not define equivalence of ICs, the author proposed these three criteria:

- Number of pads: From the point of view of probing, the number of solder pads is a key differentiator between ICs.

- Clock rate: Clock rate is a differentiator between ICs. If the contact resistance between the probe and the pad is on the borderline of acceptable/not-acceptable at low clock rates, that same contact resistance may cause functional failures at significantly higher clock rates. In addition, capacitive or inductive cross-talk between probes increases with clock rate. The complexity of probe-card design decisions to minimize cross-talk increases with clock rate.

- Requirement for testing at multiple temperatures: Having multiple required testing temperatures is a differentiator between ICs. Destined to be part of products exposed to an uncontrolled temperature environment, ICs, such as mobile phones and laptops, may be required to be tested at multiple temperatures. Compensating for the change in physical dimensions of probes with temperature, as stated earlier, is one of the challenges of designing probe-cards.

Non-Equivalence of the Two ICs

The author's expert report opined that the two ICs were not equivalent from the standpoint of probing and testing via solder-bump bond pads because:

4. Number of pads: Company B's IC had only 600 bond pads as opposed to 8,000 bond pads in Company A's IC.

5. Clock rate: Company B's IC operates at less than half the clock rate of Company A's IC.

6. Requirement for Testing at Multiple Temperatures: Company B's IC permitted testing only at ambient temperature. Company A's IC specification required testing at both ambient and 125°C.

Necessity for documentation: A complete design document package was not provided by the seller. The author opined that for such a complex endeavor, such as constructing a probe-card assembly line, documentation should specify each construction step and specify incremental tests to validate that each step has been executed properly.

Necessity for training: Training by the seller ended early and was incomplete. Among other training problems, better language translation should have been provided by the seller. The author opined that for such a complex endeavor, such as constructing a probe-card assembly line, training of technicians requires excellent communication skills.

Ultimate Resolution

The expert report was submitted, and the author was deposed by the seller's attorneys. The owner of the seller's company and seller's expert was present at the deposition. The author was asked to be present when the seller's expert was deposed by the buyer's attorney. Within hours of the deposition of the seller's expert, the author was notified that the case had settled.

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