MICROELECTRONICS RELIABILITY

Microelectronics Reliability 43 (2003) 1969–1974

www.elsevier.com/locate/microrel

Thermally driven reliability issues in microelectronic systems: status-quo and challenges

Clemens J.M. Lasance

Philips Research Laboratories, Prof. Holstlaan 4 WB 12, 5656AA Eindhoven, The Netherlands

Received 26 March 2003; received in revised form 8 May 2003

Abstract

To meet the needs of future microelectronics and microsystems, we need a paradigm shift in the approach to system reliability. It is emphasized that the scientific success of many nano/micro-related projects will never lead to a business success without breakthroughs in the way industry is handling quality and reliability through the whole value chain. The paper discusses several reasons for these facts and offers a perspective for future improvements. The paper is essentially a mix between an overview paper and some personal observations in an editorial style.

1. Introduction

A significant and increasing proportion of the initial and lifetime costs of an electronic product relates to its physical design. Much of the development cost of a new product is committed during the design and qualification stages. Consequently, optimization of the physical design before manufacturing, physical prototyping and qualification has become a key factor to competitiveness across all industry sectors. Ideally, quality prediction and optimization has to be linked to overall risk management, providing estimates of how serious a quality risk is taken when previous field experience is absent. From this, system integrators can compare the monetary benefits from increased sales and market share against the possible warranty and maintenance costs. However, this is not the current situation. Reliability is usually dealt with *after* physical prototyping. Clearly, this *experience-based* design method cannot lead to a competitive design with short time-to-market, optimized performance, low costs, and guaranteed reliability specifications. In addition, product and process design is mainly single-process and single-discipline oriented while the strong interaction effects between different processes and different technical disciplines are often ignored [1].

The question thus is: how does the electronics industry deal with the assessment of *reliability* in their final products? Hence, performance and safety (both frequently linked to operating temperatures) are excluded from the discussion. Also, the emphasis is on systems, not components. Many of today's components are very reliable, it is the interconnection with the system that causes most reliability problems [1–3]. However, common practice is to address system reliability by combining reliability data of individual parts. It is much simpler to perform statistically significant tests on a component than on a TV set, for two reasons. First, it is a question of cost. Testing of hundreds of plasma TV's costs a fortune. Secondly, single components are tested on a standard test board in a standard test environment. It is the only way, because it makes no sense to test the combination single component/standard board in a realistic user-defined environment. However, it makes no sense either to test a TV set in a standardized test environment, unless a clear correlation exists between a temperature-cycled test environment and a fully operational system in a real-life environment, which is not the case.

Having narrowed the focus to reliability only, the status-quo is that we lack the knowledge, tools and accurate input data to enable meaningful prediction of

E-mail address: clemens.lasance@philips.com (C.J.M. Lasance).

0026-2714/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0026-2714(03)00183-5

reliability. Furthermore, there is another important reason to explain the lack of progress in this field. Suppose the knowledge, tools and data are available, then the current situation in many industries is such that this knowledge cannot be fully exploited because the responsibilities for meeting the specs are not clearly defined. This issue is tackled in Section 5. After a section on trends in microelectronics, the paper discusses the gap between current practice and what is really needed to meet the requirements of the oncoming nanoera.

2. Trends in microelectronics and microsystems

Information Technology (IT) is a more than trillion dollar industrial sector. Hardware accounts for more than two thirds of the revenue. Semiconductor devices and packaging together account for up to 25% of the IT. The largest fields of application are IT peripherals (US$43 billion in 2005) and biomedics (US$20 billion in 2005) next to the other markets such as automotive, household, and telecommunications. Electronics continue to play a vital role in current and future human life and society. The future will bring a plethora of new products and processes based on new concepts with limited past experience to build upon. Examples are:

- rapid developments in telecommunications,
- automotive (ubiquitous connectivity; electrical systems are expected to take a quantum leap when hybrid vehicles begin entering the market),
- displays (LCOS, PolyLED),
- MEMS (sensors, Lab-on-Chip, energy scavenging for low power),
- lighting (LEDs to replace eventually everything from traffic lights to domestic lighting),
- healthcare (diagnostic imaging, personal health monitoring, home defibrillators),
- personal care (today's professional treatments are tomorrow's consumer products, such as photo-epilation and tooth whitening),
- Ambient Intelligence (electronics all over the place).

Microsystems form an emerging field for which worldwide markets are expected to increase by 20% annually from about US$33 billion in 2000 to US$75 billion in 2005. Typical microsystems based products with significant market shares are inkjet printheads, read/write heads for harddisks, cardiac pacemakers, hearing aids, test strips for in vitro diagnostics, pressure sensors, and accelerometers. Emerging products are micromechanical flat panel displays, components for optical telecommunication, RFMEMS, implantable drug delivery systems, biochips, and fingerprint sensors. Following a study from Chaner In-Stat/MDR, the market of MEMS components for wireless communications should increase from US$10 million in 2001 to more than US$350 million in 2005.

Up to now, industry managed to keep the reliability problems within acceptable limits, but sometimes at the cost of expensive redesigns, extended lifetime testing and in exceptional cases withdrawals from the market due to safety reasons. Bringing new products to the market, one could often rely on previous experience. While many developments related to miniaturization could be called 'evolutionary', further miniaturization down to nanoscales demands revolutionary approaches. Since the 1960s microelectronics show a doubling of data density every 18–24 months at the same costs. Currently, the density in an integrated circuit has reached approximately 40 million transistors per square centimeter. Typical dimensions (transistor's gate length) have fallen down to 130 nm and are expected to approach 45 nm by the year 2010. The thickness of dielectric layers in ICs already entered the nanometer domain with typical values of a few atoms. Not only the ICs, but also the packages, interconnections and boards show a remarkable miniaturization and increased function integration. IC packages with pin-counts of up to 1000 Inputs/Outputs with pitches down to 50–80 μm are already available. At the same time, boards have shown a transition from simple component supports with electrically conductive paths on the surface to complex multi-layered structures connected by microvias, rendering the extraction of local effective thermal conductivity data a formidable task [4].

The problems expected with the interconnectivity of the future cannot be solved by simple downscaling. For example, metals with a grain size of around 10 nanometers can be as much as seven times harder and tougher than their ordinary counterparts with grain sizes in the micrometer range. Size effects like these are known to play a significant role in miniaturization, and the implementation of these effects in future design processes is a necessary prerequisite to make optimal use of materials and structures at the nanoscale. Furthermore, surface effects are very different from bulk effects and become increasingly important. Presently the required knowledge in this area is substantially under-developed. The thermal and mechanical behavior of products and processes at nanoscales (both in space and time) cannot be predicted by conventional macro-scale continuum physics and mechanics because they do not include any peculiarities of the small-scale structure of materials [5,6].

3. We need a paradigm shift in reliability prediction

The trends imply that we run into severe problems if we continue to walk the traditional path. To meet the needs of future microelectronics and microsystems, we need a paradigm shift not only in reliability prediction but also in reliability thinking. In my opinion, the scientific successes of many nano/micro-related projects will never lead to a business success without breakthroughs in the way industry is handling quality and reliability through the whole value chain. Radical innovations are mandatory because of the following reasons:

- The currently available theoretical and experimental methods and tools for reliability are mainly developed for macro-scale situations and largely based on concepts that can be traced back to the Germanium age [7]. It should be understood that an evolutionary approach is not sufficient, we need a revolution in science as well as in standards.
- Product/process design has mainly depended on the designer's experience. Often, up to 10 cycles (material development, concept designing, building and testing multiple physical prototypes) are needed, with some qualitative support from numerical simulations. Lifetime testing with duration of 6 months is no exception.
- The current guidelines for lifetime prediction of systems usually focus on summing the estimations for the individual parts, thereby neglecting the effects of interconnects, mutual coupling and system boundary conditions. This practice usually leads to overly conservative designs that are no longer an option for competitive future micro- and nanosystems.
- Temperature is a vital factor in microelectronics and microsystems reliability. Current practices are based solely on steady state single-point temperatures whereas temperature gradients in space and time rule reliability at moderate temperatures up to 150 °C [7–12].
- The current reliability paradigm cannot cope with the strong size effects in both geometric and time scales [5].
- When design margins are reduced to finally reach the physical limits (especially in natural-convection dominated systems) the current design methods become quite dangerous for the business. In addition, the increase in outsourcing to reduce costs will add margins, simply because every added link in a chain demands an extra margin. Hence, Supply Chain Management will play an increasing role. With shrinking design margins, current reliability protocols will frustrate the co-operation needed to optimize the reliability of the product at the end of the chain.
- From a social point of view, quality has an ever-increasing impact on human life and society. Undesired and uncontrolled quality will cause significant damage to environment, quality of human life, and sustainable development. Just imagine what happens if MEMS and other microsystems are everywhere while the reliability per component, at best, does not change.

In summary, future reliability approaches should be based on physics, not religion.

4. Research challenges to cope with future reliability demands

In order to address the problems mentioned before, we need significant research efforts in the six areas indicated below. It should be added that part of the proposed research is already ongoing, and some companies are clearly ahead in applying early results in their product creation process.

1. *Materials Research*
   Acquisition of fundamental knowledge (both theoretical and experimental) and technologies for design, synthesis, characterization and modeling of new robust and compatible materials, to provide the desired properties according to the specific application needs and reliability specifications.
2. *Thermal Physics*
   Theoretical, numerical and experimental analysis of heat transfer in (submicron) electronic parts and systems, e.g. limits of continuum-physics, anisotropic thin film thermal properties, in situ measurement of thermal properties and (dynamic) compact modeling. While we have booked serious progress over the past years [13,14] we are still a long way from achieving the accuracy we need for meaningful reliability prediction [4].
3. *Multi-scale mechanics*
   Acquisition of fundamental knowledge and techniques for micromechanics and nanoscale measurement methods, including novel ways of extracting mechanical material properties at nanoscales. Also software to predict material behavior based on molecular mechanics should be mentioned.
4. *Reliability testing*
   Virtual qualification and prototyping is only possible if all failure mechanisms, initial and boundary conditions and material properties are sufficiently well known [15]. Standard practice is to address lifetime through various kinds of accelerated tests, all based on temperature cycling. We need novel techniques based on mechanical loads, power cycling or other means of generating local temperature gradients to specifically address a particular failure mechanism. Additionally, we need alternatives to the time-consuming lifetime tests [16]. On the long run, the only feasible solution is to replace these tests by numerical predictions.
5. *Standardization*
   Since the introduction of area-array style packages, we see a major shift from a component-only approach to

an integrated board/system level approach. An important consequence for reliability management is that package interconnection at the system level needs to be addressed. Responsibility for the final system reliability should be shared between component manufacturers and system makers. Such an approach requires a paradigm shift in reliability thinking, such as acceptance by the component manufacturers of responsibility to generate validated data and models to be used by system makers, and of system makers to understand the data and use of the models. It is expected that co-design will be the preferred choice for future product development. It is obvious that Supply Chain Management will play an increasing role when quality has to be improved. Suppliers should at least conform to the same quality requirements as the system vendor. While certainly some progress has been realized, we are still far away from worldwide standardization.

6. *Software*

Integrated and industrially applicable methodologies and tools should be pursued to predict, evaluate and optimize the product and process behavior prior to qualification tests or even major manufacturing investments. Such software should be commercially available, allowing the end-users to link their proprietary knowledge to provide them with a competitive edge.

5. The question of responsibility for meeting the temperature specifications

The issue of responsibility is not often discussed but it offers an explanation for the slow adoption of new developments by many industries. Recently, Belady summarized the role of thermal management in the design process quite nicely [17]:

> *The ultimate goal of system thermal design is not the prediction of component temperatures, but rather the reduction of thermally associated risk to the product.*

However, many designers are quite satisfied when the component temperatures stay within some (often untraceable) limit, usually some maximum junction temperature, because they take it for granted that reliability issues can be solved using a set of simple design rules. Well, electronic design is not simple, mechanical design is not simple, and so is thermal design. Basically, the misunderstanding is caused by the fact that usually electronic designers are held responsible for meeting the temperature specifications. While these designers are very capable of solving complex electronic problems, they lack a background in heat transfer. Hence, the call for simple design rules. Rule 1 of the Bible of the Association of Simple Spec Believers states the following: "*For every 10 °C increase in temperature the failure rate doubles*". Rule 2 is: "*Thou shall not read other Bibles.*", explaining the fact that Rule 1 is repeatedly quoted even in serious journals. Rule 3 is a consequence of Rule 1: "*Thou shall lower the temperature.*"

The basic problem is that most of the current temperature specifications only deal with absolute values of component temperatures. It should be realized that device junction temperature is only a meaningful metric for *performance*, not *reliability*. The reason is that most commonly occurring failure mechanisms are not related to single-point absolute temperatures, at least not below say 150 °C [1,4,6,9]. A common failure mechanism such as electromigration is a complex function of temperature, but it requires a spatial temperature gradient [8]. Hence, the argument that electromigration depends on some maximum temperature is at best not the whole truth. Another example concerns solder joint fatigue caused by temperature variations in time and space, obviously not by steady state temperatures (with the exception of the influence of creep). Hence, to specify a maximum solder temperature is *not* correct; it would be much better to specify a maximum temperature *sweep*. Another reason to revisit current solder specs is caused by ongoing miniaturization that increasingly causes power cycling to introduce an additional temperature difference between package and solder that is not captured by temperature cycling. Finally, it is important to realize that it is very well feasible to *increase* the temperature of the junction and to *decrease* at the same time the thermo-mechanical load over the interconnect by appropriate design changes.

Another consequence of oversimplification is that it is difficult to get funding for thermal research, because designers are forced to belief that if they do exceed some temperature the design is not OK. Experienced designers know from practice that this is not true. Very rarely thermal issues could directly be related to field problems except for products that rely on performance such as microprocessors. Apparently there is no *direct* profit to be gained by pumping money in thermal research. Hence, especially when economy is down, thermal gets no priority. The fact that disasters do not occur (with some exceptions that are not published) means that design margins are still pretty large and that most designs are overly conservative. But, as stated before, margins are steadily reducing. A prerequisite to improve this situation is to move the responsibility for meeting the specs to the mechanical designer. Of course, the electronic engineer stays responsible for reducing the *dissipation*, but doing such is quite different from reducing the resulting *temperature*. The relationship between dissipation and temperature is the subject of rather complex heat transfer theory, and hence the domain of the mechanical engineer.

Some people argue that thermal problems will be solved in due time by appropriate technical means such as power reduction, high thermal conductivity materials, etc. However, history teached us an important lesson. When CMOS was introduced in the eighties, some expected that thermal problems would be gone forever. The fact is that every new technology that reduces thermal problems will create a new opportunity for electronic designers to bridge the gap again. But the best argument to apply state-of-the-art thermal expertise right from the start of a new design is that eventually this product could reach the market earlier and could be cheaper and smaller.

6. My crystal ball. Thermal experts: Beware!

The question is not *if* disasters will occur, but *when*. Companies who believe in simple thermal design rules will eventually loose the battle, simply because their wiser competitors will be earlier on the market with more reliable and cheaper products. In a claim culture, the chances are high that these companies will sue experts who keep preaching the bible of simple thermal design rules. So, how to prevent lawyers coming after you? By acknowledging the following wise words by Einstein:

Everything should be made
as simple as possible,
but not simpler.

Let us stop preaching that system reliability can be addressed by a simple maximum temperature criterion, because:

- it is often disputable,
- specifications that *do* matter are not addressed,
- it keeps designers ignorant,
- it gives managers a false illusion of safety,
- it hampers design optimization.

A steady state single-point temperature is in most cases not physically linked to the failure mechanisms that dominate the reliability of electronic systems. Of course, there exists a link between this temperature and a temperature gradient. By decreasing the temperature, usually also the gradients become smaller. However, this is quite different from optimizing the design with the objective to lower the local temperature gradients. Doing so might well result in higher operational temperatures.

7. Conclusions

To face the many reliability problems that are foreseen for the future we need breakthrough approaches in many different disciplines. It is only through integration of the results of the various research areas to culminate in one virtual prototyping tool that electronic industries are able to predict, evaluate and optimize the product and process behavior and reliability prior to qualification tests and major manufacturing investments. Additionally, standardization of physics-based temperature specifications agreed upon by everyone in the supply chain becomes a major issue.

Finally, thermal experts should stop preaching that designers do a good job if they try to keep the temperatures of critical components below a certain specified value. It is a dead end.

Acknowledgements

The author appreciates the discussions with Prof. Kouchi Zhang of Philips CFT and his contributions to the contents of this paper. He also remembers vividly the inspiring discussions with Prof. Mike Pecht of CALCE a long time ago, opening his eyes for the remarkable things that rule the world of temperature specifications.

Appendix A

People who are considering to quote Rule 1 ("*For every 10 °C increase in temperature the failure rate doubles*") in their paper to get funding for their thermal activities might benefit from taking notice of the following poem (after Shakespeare's Macbeth):

Poor old Rule 1

It's but a walking shadow, a poor player,
That struts and frets his hour upon the stage,
And then is heard no more; it is a tale,
Told by an idiot, full of harm and danger,
Signifying nothing.

They might also benefit from consulting [18].

References

[1] Parry J, Rantala J, Lasance C. Enhanced electronic system reliability—challenges for temperature prediction. IEEE CPT 2002;25(4):533–8.

[2] Bailey C. Modelling the effect of temperature on product reliability. In: Proceedings of SEMI-THERM XIX, 2003. p. 324–31.

[3] Luiten W. Sense and nonsense thermal requirements. In: Proceedings of SEMI-THERM XIX, 2003. p. 332–5.

[4] Lasance C. The conceivable accuracy of experimental and numerical thermal analyses of electronic systems. IEEE CPT 2002;25:366–82.

[5] Zhang GQ, Tay A, Ernst LJ. Virtual thermo-mechanical prototyping of electronic packaging—bottlenecks and solutions of damaging modelling. In: Proceedings of 3rd

Electronic Packaging Technology Conference (EPTC), Singapore, 2000. p. 263–70.

[6] Zhang GQ, Ernst L, Tay A, et al. Virtual prototyping: challenges in material characterisation and modelling. In: Proceedings of 51st International Conference of ECTC, USA, May 2001. p. 1479–86.

[7] Pecht M. Why the traditional reliability prediction models do not work—is there an alternative? Electron Cool 1996;2(1):10–2.

[8] Jackson M, Lall P, Das D. Thermal derating—a factor of safety or ignorance. IEEE Trans CPMT, Part A 1997; 20(1):83–5.

[9] Lall P, Pecht M, Hakim E. Influence of temperature on microelectronics and system reliability. New York: CRC Press; 1997.

[10] Das D. Use of thermal analysis information in avionics equipment development. Electron Cool 1999;5(3):28–34.

[11] Humphrey D, Condra L, Pendsé N, Das D, Wilkinson C, Pecht M. An avionics guide to uprating of electronic parts. IEEE Trans CPMT, Part A 2000;23(3):595–9.

[12] Osterman M. We still have a headache with Arrhenius. Electron Cool 2001;7(1):53–4.

[13] Lasance C. The European Project PROFIT: prediction of temperature gradients influencing the quality of electronic products. In: Proceedings of 17th SEMI-THERM Symposium, 2001. p. 120–5.

[14] Lasance C. Highlights from The European Thermal Project PROFIT, accepted by IMECE'03, Washington, DC, 16–21 November 2003.

[15] Lindell M, Stoaks P, Carey D, Sandborn P. The role of physical implementation in virtual prototyping of electronic systems. IEEE Trans CPMT, Part A 1998;21(4): 611–6.

[16] Radivojevic Z, Abdul_Quadir Y, Myllykoski P, Rantala J. Reliability prediction for TFBGA assemblies. In: Proceedings of SEMI-THERM XIX, 2003. p. 336–40.

[17] Belady C. Effective Thermal Design for Electronic Systems. Hewlett-Packard Company, 22 June 2001.

[18] Kordyban T. Ten stupid things engineers do to mess their cooling. Electron Cool 2000;6(1).