40. FAILURE ANALYSIS AND EPILOGUE

40.1 Review/Background

Throughout the lectures in this course, we covered a lot of materials about various issue in terms of device reliability. The beginning of this course was the discussion about physics as a researcher mode. But in life, first time you go into the trouble researcher mode goes away and you have to deal with real emergent situation. No matter how sophisticated you are and how much experienced you have, there always is a failure to encounter. Learning how to examine those failures and learning from our mistake is the first thing you should do.

When most people say they are doing reliability analysis, most of time they are doing failure analysis which is essentially a forensics of the failed devices. To do that, there are huge set of equipment which will be briefly mentioned in this lecture.

40.2 Failure Case Studies

In this section we discuss several examples of massive failure happened in the history. The first story is about the failure of IBM chip due to the radiation damage in 1987. During the fabrication process we generally use various kinds of chemicals to clean the surface of semiconductors. After a thorough investigation IBM found that the person who was doing a job of cleaning the bottles on which the chemicals are stored had been contaminated by Polonium. Tiny depositing of Polonium cause a massive failure in device operation since it is a highly radioactive source thus the electrostatics of transistors can be messed up. It was one of the reasons why IBM gradually moved to SOI structure which is much more robust to those radiation exposures. As we can see, minor
mistakes can cause unexpected failure. For example, Intel is very particular about the suppliers. When they construct a new fabrication facility they copy even the carpet, which emphasizes the fact that minute details always matter.

Secondly, it’s a story about liberty ships. During Second World War German U-boats had torpedoed a huge number of enemy ships. So the U. S. who had been supplying the cargo ships had to make more ships in a short period of time. In order to accelerate the manufacturing process they used welding instead of bolting in making a boat. The result was, however, those ships were running fine and then all of sudden it broke up into two in the ocean or experienced serious defects. Of course they had to carefully investigate the problem and recall the already produced ships to repair them. But do you understand the problem of welding? If you bolt something, crack cannot propagate from one plate to its neighboring one. If you weld these things, on the other hand, it can easily propagate and cause a macroscopic failure.

The third example and at the same time most interesting failure story is about Comet airplane accident in 1950s. The brand new and first commercial civilian jet airplane suddenly burst into parts at 12,000 m over the Mediterranean Sea. After painstaking efforts of collecting wreckages across the ocean they realized multiple causes of accidents. Main cause was something called metal fatigue. Since the airplane went up to very high altitude the fuselage underwent a repeated stress of pressurization. In addition, there were initially small crack generated due to the process of riveting. The problem of riveting is that it will make small cracks when they punch through the place to make a window, for example. Lastly, those small cracks at the sharp edges of the windows became bigger and bigger due to the constant stress coming from high pressure difference at high altitude. Those metal fatigue beginning from the window corners were responsible for the catastrophic disaster.

Last example is about the accident called ‘Hyatt Regency walkway collapse’. In Figure. 40.1, two possible structures for hanging walkways in the air are described. The left one was the original design and the right one was the modified one. As you can see in the original design the stress the nut should stand is only P. But the modified one, in which a new subsequent pole is hanging on the other part of the structure, had a defective structure since it is like a person hanging by grabbing your leg and you have to pull him including yourself. As a result the stress applied to this nut became doubled. Such a minor change caused this massive collapse and killed 114 people [1].
40.3 Instrumentations

When failure happens you have to investigate and find out what went wrong. One thing that we have to keep in mind is that the forensics or finding out what made our system collapsed is as important as to understand the fundamental physics of reliability. And there are various tools and instrumentations that can help you during that process.

<table>
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<tr>
<th>Microscopes</th>
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Figure. 40.1 Hyatt Regency walkway collapse, Oct. 14, 1978 [1]
### 40.4 Defects and Coordination

In this part, we discussed that Crystalline, poly-crystalline, and amorphous materials all have a broad range of applications in IC industry. They appear very different initially.

Also, we learned that amorphous material is not really random and it is easy to calculate the size-distribution from elementary theory.

Moreover, we discussed how Euler and Maxwell relationships help in understanding coordination and defect formation. An amorphous material need not be defective. Amorphous Si has fewer types of defects, but more of them.

### 40.5 NBTI Degradation

We have seen how NBTI is PMOS specific problem. Using reaction-diffusion model of Hydrogen atoms initially annealed at the Si-SiO₂, degradation is described using power...
laws. In addition, Frequency independence nature is analyzed and verified using experimental techniques. Moreover, NBTI can heal itself due to the re-passivation process of H atoms diffuse back to the interface. This in its turn gives rise to sophisticated measurement technique (on the fly) to avoid relaxation during measurement. Complex field acceleration factor due to the barrier lowering and non-Arrhenius temperature activation are also discussed.

40.6 **HCI Degradation**

Unlike NBTI, both NMOS/PMOS may be affected. The tail of electron distribution will be energetic enough to cause impact ionization. Accordingly, HCI is still a concern even with voltages close to 1V. Both Hydrogen and Oxygen atoms are the culprit for degradation. Time-Universality is a key feature. Using universal scaling theory, hot carrier driven voltage acceleration can be obtained. Anomalous temperature acceleration (negative temperature coefficient) is discussed. Since HCI doesn’t relax, this gives proof of Si-O involvement in the degradation. Device design like lightly drain doped (LDMOS) and circuit solutions are effective.

40.7 **TDDB Degradation**

TDDB was NMOS issue historically but it becomes now predominately PMOS feature due to the minority impact ionization. The exact mechanism of time dynamics is still under investigation. Anode Hole Injection is used to describe the voltage acceleration. We have seen how soft breakdown due to energy relaxation allows significant improvement in lifetime. While for Thick oxides the breakdown becomes correlated.

40.8 **Radiation damage**

Radiation damage is a challenging problem that has gotten worse with scaling. The error modes associated with older technologies have been replaced with new issues for modern systems. Understanding the new modes is essential in combating radiation
concerns. Circuit solutions like ECC and system redundancy and multi-cycle computing has been particularly effective.

40.9 Measurement

It is crucial to Learning different characterization techniques and failure analysis to understand the fundamentals of measurement theory. Developing characterization techniques and theory behind them is as important as developing reliability theory itself. We have discussed the difference between on-the-fly and stress-measure-stress experiments. Often it gives very different results due to relaxation during the measurement itself (e.g. NBTI). In addition, different methods are discussed for interface trap characterization like Charge pumping method, DC-IV measurement and Idlin. For bulk defects responsible for TDDB, we discussed methods like Stress-Induced Leakage Current (SILC) and Quantum Yield (QY).

40.10 Data Analysis

Distribution has to be physical; therefore it is better to derive the distribution from physical principles (e.g. blind fish in river with waterfall). Data plotting is a key for data analysis. Hazen formula, Kaplan formula (handling censored data) allows unbiased plotting.

Maximum likelihood estimation (MLE) is the most effective for fitting the nonlinear data. We should always get error bounds and keep the number of parameters to a minimum. Larger number of parameters improves the fit but the model loses a lot in terms of predictivity and physical meaning. Different formulas are discussed like AIC to account for the penalty for number of parameters. Finally, Design of experiments is very helpful to get the important parameters and reduce the number of needed experiment to investigate any physical problem.
40.11 **Epilogue: A contentious field because theory matters**

Like many field in natural sciences, the theory enables long term projection. For example, if theory for estimating the device lifetime is wrong, the whole company will be bankrupt due to the huge amount cost for maintenance and replacement. On the other hand, if the theory is overly conservative, which can ensure a long device lifetime in sacrifice of device performance; the whole company will also be bankrupt. Therefore, data should be vetted carefully over and over again to ensure validity of model projection. We developed a theory of physical reliability to complement the work on Statistical and Empirical reliability already present. Our hope is the make the topic as scientific and as broadly accepted as ‘Fracture Mechanics’. Hopefully, you have learned something about extreme non-equilibrium statistical mechanics that you will be able to use in wide variety of situation.

40.12 **Bibliography**