Semiconductors and Pre-Failure of Electric Circuits Under Dynamic Thermal Shock

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(Dated: 19 March 2021)

The goal of this research is to evaluate the effectiveness and accuracy of the Shockley Diode Equation with the specific focus of investigating any potential shortcomings in the equation in situations involving extreme thermal conditions. The Shockley Equation

$$I = I_s(e^{V_D/\eta V_T} - 1) \tag{1}$$

is used for defining the I-V characteristics across a diode. Modifications to this equation have been made to account for ideal vs. real diodes (material imperfections as a factor of ideality) and final voltage resulting from the inclusion of a parasitic resistor typical in a diode circuit setup. These considerations have a voltage-centric focus. However, we seek to explore the influence of temperature on the functionality of PN-junction diodes and circuitry, as thermal effects are a failure mechanism within these components that may become more problematic as demand for smaller, faster devices continues. Our research intends to focus on pre-failure indicators within a semiconductor circuit design that may result from thermal activity within the diode circuit, as well as dramatic ambient temperature changes.

Keywords: PHYS222;Shockley, diode, temperature, thermal behavior, thermal failure, thermal shock, pre-failure

I. INTRODUCTION

As different forms of electric and computer technologies are developed and utilized, there is an increasing demand for faster, smaller electronic devices and components. Therefore, electrical and computer engineering have directed efforts to increase speed and miniaturization. The subfield microelectronics was born from this demand, primarily focusing on manufacturing and analysing small scale circuits and components comprised of semiconductor material.[15] Microelectronics comes with its own set of challenges, the most significant being thermal shock and power dissipation.

Thermal shock is the disparity between expansion and contraction at extreme and rapidly changing temperatures. Microelectronic devices are usually built with semiconductor material, which are especially susceptible to thermal shock because they have low coefficients of thermal expansion.[4] Thus, progress in increasing speed and miniaturization is bounded by material stresses under thermal shock. Power dissipation is the heat produced when something experiences a loss or waste of energy. Increasing the speed of electronic components and devices leads to increased heat production which in turn means higher power dissipation is needed. However, power dissipation is uniquely challenging in microelectronics because it is difficult to determine the origin of a heat source in small scale units, as a probe will likely be larger than the device itself. This means the probe will have a direct impact on the temperature. A precise measurement becomes impossible.[9] High speed miniaturized electrical devices are thus vulnerable to thermal failure. The microelectronics subfield faces diminished design performance, shortened life span of circuit materials, increased consumer cost, and environmental waste.

Thermal failure research predominantly looks at endpoint failures in semiconductor materials, and remedies are typically derived from analysis of this endpoint failure. A common research methodology is to push devices past their breaking point using thermal cycling. In thermal cycling, the temperature is increased and decreased repeatedly until thermal fatigue is observed. Data is collected and used to determine the conditions under which device failure occurs, a range of acceptable conditions is then established, and an expected lifespan is derived (assuming operation under those conditions).[13] Other research has revealed that thermal cycling tests do not take power cycling into consideration, and developed a power cycle test where the power to a device is repeatedly switched off and on. While this research found estimated device lifespans were shorter when the power cycle test was applied, it was not able to shed light on semiconductor thermal behavior prior to endpoint thermal fatigue.[13]

Another methodology employed is thermal modeling. "Thermal resistance may be used to form simple models to compute steady state operating temperatures for a circuit... With the addition of thermal capacitance, transient conditions may also be accurately modeled."[11] Electrical circuit analysis tools are also used to perform thermal analysis of circuit components. However, electrical circuit analysis tools such as SPICE use the lumped-element model. This works for electrical circuit analysis because current flow is restricted to defined paths. Thermal paths, on the other hand, are not so restricted. Using software like SPICE to conduct thermal analysis is imprecise because thermal components must be lumped to perform the analysis (like electrical circuit components) even though " defining lumped thermal components is often an exercise in estimation, intuition and tradeoffs."[8]

Regardless of the tests applied, knowledge of semiconductors' lifespans and failure modes are derived from endpoint failure analysis. In other words, when thermal failure occurs in semiconductor materials the causes are investigated. Manufacturers use this information to provide details of reliable operating parameters, including ranges of temperatures, humidity, and voltages. This post-mortem approach can only diagnose thermal failure when it occurs in existing devices; it cannot preemptively correct or prevent thermal failure. Determining pre-failure behaviors in semiconductors would improve performance and be more cost effective. Instead of using endpoint failure analysis to establish strict environmental parameters that a device may operate within, electrical and computer engineers could design products with adaptive mitigation schemes, such as server offloading or other hardware task sharing. We present here our work on characterizing nonlinear changes in semiconductor circuit performance due to thermal shock in the pre-failure regime.

II. DEFINING KNOWLEDGE

In order to begin testing semiconductor circuits for thermal pre-failure characteristics, our research needed to cover how semiconductors function. For this research, we focused on the widely used Shockley Diode Equation, as it is a defining equation for the common semiconductor unit, the PN-junction diode. The equation is used for calculating the I-V relationship across a diode and is utilized in modeling simulated circuits. Due to the influence that temperature has on the thermal voltage variable in the Shockley Diode Equation, we are interested in testing the accuracy of the equation in simulation as we subject a physical diode circuit to varying thermal stresses. If any inaccuracies are observed in our experimentation, it may indicate that any semiconductor component design based off of simulations implementing this equation may be under-equipped to tolerate real world temperature range possibilities. Here we define the Shockley Diode Equation and the PN-junction diode.

The Shockley Diode Equation, or The Diode Law was created in 1949. It was formed as a result of works published by the Bell Labs Technical Journal. The equation was derived by William Shockley, who had previously co-invented the Shockley diode, for Bell Telephone Laboratories, a major science factory. This equation demonstrates the ideal behavior of a Shockley PN-junction diode.[6] Below is a common representation of the Shockley Diode equation:

$$I = I_s(e^{V_D/nV_T} - 1)$$

- I = diode current
- I_s = saturation current (reverse bias)
- V_D = voltage put across diode
- V_T = thermal voltage defined as kT/q *(Boltzmann constant, pn junction absolute temperature, electron charge. Approximately 25.8563 mV at 300K)*
- n = *emission coefficient* or *ideality factor* [16]

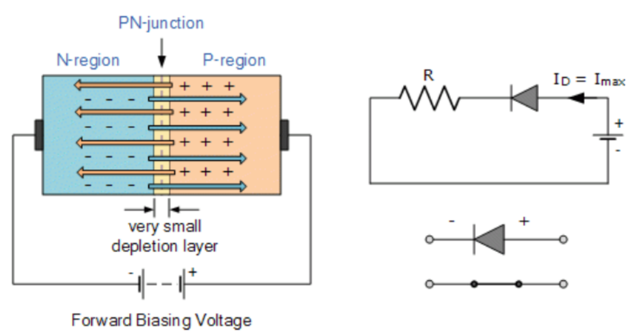
Variation of equation representation using value of V_T:

$$I = I_s(e^{q_e V_D/nkT} - 1)$$

However it is written, the equation demonstrates the relationship:

$$I = I_s(e^{\frac{(PotentialEnergy)}{(ThermalEnergy)}} - 1)$$

PN Junction Diode - nonohmic, mono-crystalline semiconductor device that passes current in a single direction as a result of its physical construction. A p-type semiconductor and an n-type semiconductor are either fused together or a single piece of semiconductor material is infused with n-type and p-type doped regions, which leads to a potential barrier voltage being created at a junction region.[1]



[3]

A. Thermal Activity and Effect of Heat on Diode

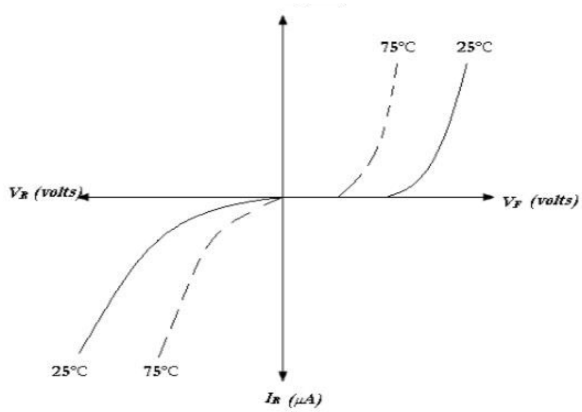
Forward voltage V_F in a diode decreases as temperature rises. When extrapolated to high enough temperatures - about 325 Celsius - V_F approaches 0V. Issues resulting from high junction temperature include the risk of:

- Increase in breakdown voltage threshold
- Increase of leakage current

Component	Mfr	Part	Status
PN Diode	ON/ Fairchild	1N4148	Received
Op Amp	Analog Devices	OP27GPZ	Ordered
Voltage Regulator	ON Semi.	LM317BTG	Ordered
Breadboard	RexQualis	RQ-BK-002	Received
Resistors	TBD	TBD	TBD
PNP Transistors	TBD	TBD	TBD
Potentiometer	TBD	TBD	TBD
Voltage Source	TBD	TBD	TBD

- Increase of mechanical stresses
  [8]

These issues resulting from excessive temperatures pose a problem when the conditions for effective conductivity are affected. This relationship between temperature and a diode's current/voltage are illustrated below:



Effect of temperature on V I characteristics

[12]

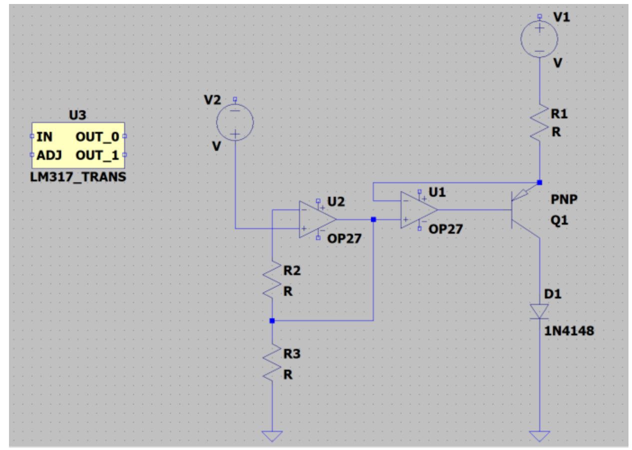
As the temperature rises, it can be observed from the graph that the forward voltage breakover threshold decreases, meaning current can begin flowing at a lower voltage requirement. This can result in unreliable or erroneous signals, or thermal runaway where the increasing temperature produces increased current through the diode, which leads to more increases in temperature and so on. This latter feedback scenario can lead to permanent component and circuit damage.

III. EXPERIMENT

A. Materials

Currently, we have compiled a short parts list that needs to be completed with the missing components necessary for a functional test circuit. Additional knowledge is required to better understand which particular components and tools should be ordered for our experiment apparatus.

B. Methods and Procedures



Our preliminary design for our simulation circuit, which will also serve as the design for our physical experimental circuit is shown above. Collectively, there is more we need to learn with regard to how the discrete components serve the overall circuit to better understand the effects we can generate on the diode. As of now, we are able to import design details for specific components into the LTSpice library so that we can instantiate the products we intend to use in our physical circuit.

In order to test the effectiveness of the Shockley Diode equation, planning would begin with the assembly of a physical test circuit as well as a digital circuit replication of this circuit in the LTSpice program. We would then need to do preliminary measurements of each of the components to acquire the actual, accurate individual properties before experimentation takes place.

A current source would also need to be designed and integrated into the circuit to ensure a constant and controlled flow of current into the system. We would then be able to test the physical circuit under varying levels of both voltage and current and replicate these conditions with the digital circuit in LTSpice.

IV. FUTURE WORK

The initial phase of our research efforts has been focused on establishing foundational subject matter knowledge amongst the team, as well as seeking consultations for proper circuit assembly for our experiment design. Moving forward, we will continue building upon our foundational knowledge by attending supplementary instructional sessions. These sessions will also aid in supporting our prior research and experimental efforts. We also plan to conduct trials on physical circuits to observe the real world consequences of thermal shock, as simulated by the LT Spice program. The data we would collect from these trials would then be analyzed against the simulation trial data to determine if the results match. The conclusions we draw will be based on these results and will either further prove or disprove the accuracy of the Shockley

Diode Equation.

V. ACKNOWLEDGEMENTS

We would like to thank Professor Tom Fleming of the Physics department at Edmonds College for his help and continued guidance. We would also like to thank Dr. Tucker Howie of the Edmonds College Engineering department for his consults and advice.

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