Modeling PIN Diode Temperature Rise in High Induced Current MR Receive Coils

Robert Caverly[1], Ronald Watkins[2], and William E Doherty[3]

[1]*Villanova University, Villanova, PA, United States,* [2]*Department of Radiology, Stanford University, Stanford, CA, United States,* [3]*Microsemi, Lowell, MA, United States*

ABSTRACT: Ultra Low Magnetic Moment (ULM) PIN diodes have been studied using a new electrothermal SPICE-based circuit simulation model that predicts both electrical and thermal behavior of PIN diodes used in high field and high induced RF currents MR imaging. The model for PIN diodes used in MR scanners is presented and is applied to a 1.5T receive coil as an example. The model accurately predicts the temperature rise in blocking applications and is fully compatible with industry-standard simulators such as SPICE as well as it variants and is faster than numerically-based models. Knowledge of the temperature rise in PIN protection diodes is important to coil designers because failure rates of these devices dramatically increase if temperatures exceed approximately 150 °C, with a potential loss of patient and equipment protection.

MATERIALS & METHODS: Glass-encapsulated SOGO passivated[1] ULM PIN diodes have been extensively modeled using an isothermal SPICE-based model based on the underlying physics governing the switching behavior, and this model has now been updated to include the impact of temperature on the PIN diode characteristics. The updated electrothermal model consists of three major parts; one part utilizes the standard PN junction SPICE model and a new portion that models its temperature dependence; the second describing the forward bias behavior is derived from the basic semiconductor transport equations[2] and includes the devices thermal characteristics (thermal resistance and time constant); and the third part models the isothermal voltage-dependent capacitance and conductance in the reverse bias state[3]. The PIN diodes modeled in this work had temperature characteristics that varied from highly sensitive to temperature rise to those with lower sensitivity. Prior research shows that the I-region carrier lifetime's temperature coefficient helps govern the thermal behavior and is dependent of the surface passivation and diode cross-section[4]. A commercially available ULM fast switching PIN diode with narrow I-region (approximately 6 µm) in a discrete, anti-parallel pair is modeled as an example, but the model is robust enough to be used in other MR PIN diodes. These fast PIN diodes are designed to turn on during the leading side lobe of the (SINC X) envelope for both 90^{O} flip angle pulse and the 180^{O} phase reversal pulse. The ULM diodes are also used to protect surface coil receive modules from high power RF transmit pulses. Fig. 1 shows the circuit schematic of the simulated MR 1.5T receive coil with excitation applied across capacitor A; this current excitation models the inductively coupled B1 field onto the coil. In Fig. 1, the PIN diode (50 °C/W die to package thermal resistance from the data sheet) is passively activated by the induced RF current above a certain level and the resulting temperature rise of the device is shown for five induced RF current amplitudes (Fig. 1b). The steepest and highest temperature rise is noted for the 8A RF pulse, and only lasts for the duration of the applied RF pulse, with the diode cooling off during the transmit off phase; if the transmit pulse duration were significantly longer, diode temperature could potentially rise to levels that can lead to burn-out (approximately 150 °C). Fig. 2 shows results of SPICE-based modeling of the level of blocking and temperature rise of this diode. Fig. 2 shows that, depending on carrier lifetime temperature coefficient (m), the blocking level at high induced RF currents (above approximately 2 A/35 dBm) can vary by several dB; the level of temperature rise is also a function of the thermal resistance (theta). Fig. 3 shows simulated and measured temperature rise of the ULM PIN diode die versus continuous (CW) applied power; the temperature data is de-embedded from surface temperature measurements assuming a package thermal resistance of 3.5 °C/W. The temperature increases above 20 dBm applied power, with the temperature approaching 140 °C at 37 dBm input power, a potential device burnout power level that could lead to loss of patient and equipment protection.

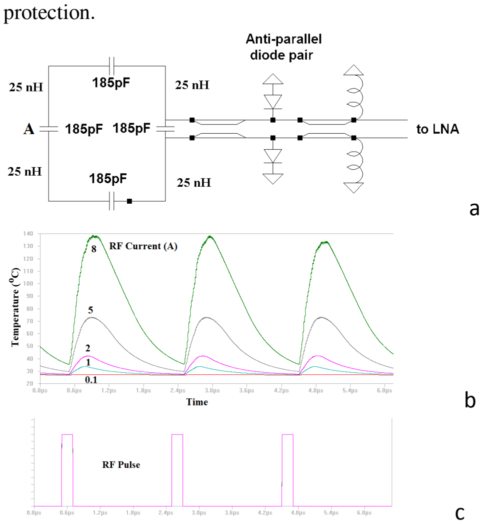

Fig. 1. a) circuit schematic diagram; b)transient temperature rise and fall in a 1.5 T receive coil when c) excited with a 10% duty cycle MR pulse**.**

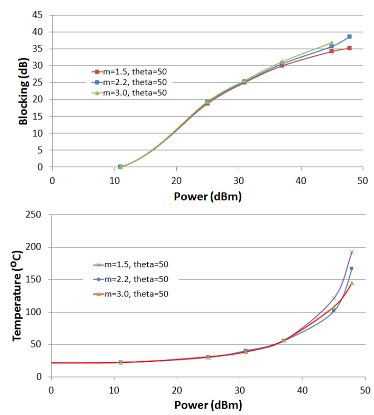

Fig. 2. Blocking and temperature rise as a function of power across a receive coil PIN diode protection circuit for values temperature coefficient values. The carrier lifetime temperature coefficient m impacts the blocking level and temperature rise.

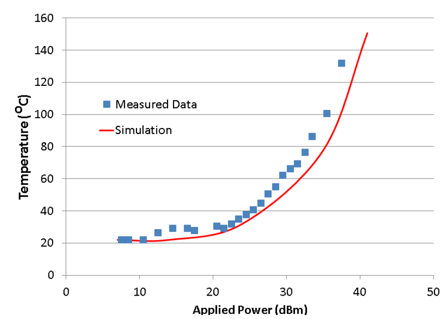

Fig 3. De-embedded temperature rise of ULM PIN diode die in an anti-parallel pair as a function of input power. Both measurements and simulation show that the diode temperature approaches 150 °C as the power level approaches 37 dBm (5 W).

RESULTS & DISCUSSION: An electrothermal SPICE-based model is shown that accurately models temperature rise due to applied RF power in ULM PIN diodes for MR scanners. The model is applied to a 1.5 T anti-parallel pair receive coil protection circuit and shows that, depending on the diode temperature coefficient, blocking can increase or decrease with increasing device temperature. Short MR pulses allow the diode to cool between pulses but high duty cycle MR pulses; this impact on diode heating and duty cycle is another variable that pulse sequence designers should include in duty cycle optimization. An Excel spreadsheet that calculates the SPICE subcircuit model[3] based on electrical and physical parameters is available at SourceForge.net (Public Domain License): http://sourceforge.net/projects/pindiodemodel/files/

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