SAND2011-2476C

Infrared Laser Interaction with SOI Transistors

Ron M. Potok
Solyndra, LLC

Rama R. Goruganthu
Advanced Micro Devices

M. R. Bruce
Consultant

Ed Cole, and Pai Tangyunyong
Sandia National Laboratories

Abstract—One common technique used in soft defect localization, analysis, and debug of silicon microprocessors is to induce a change in device performance by applying a focused laser to the circuit. In this paper, we quantify changes in partially depleted silicon-on-insulator (PD-SOI) transistor parameters such as threshold voltage (V_T), mobility (μ), and parasitic bipolar junction transistor action due to illumination with either a 1064nm laser or a 1320nm laser. We find a dramatic reduction in V_T due to a laser-induced floating body effect unique to the SOI transistor. Under 1064nm laser illumination, we demonstrate enhancement of drain current, I_d, at all drain and gate voltages, V_d and V_g, due to a V_T shift of up to 30% for an NMOS transistor and a shift of up to 14% for PMOS transistors. For a 1320nm laser, a small V_T shift ($\leq$ 6%) enhances I_d at low V_d and V_g. Above a crossover voltage in V_d and V_g of around 0.8V (depending on doping and channel length), I_d decreases due to laser heating degrading μ by ~ 2%.

Index Terms—SOI, floating body effect, MOSFET, laser

I. Introduction

One common technique used to localize and study soft defects in silicon-based microprocessors is to raster a focused laser over a chip while running a pattern on the circuit. When operating the device near a pass/fail operating condition, laser light will locally interact with a targeted transistor (either enhancing or degrading its performance) and change the pass/fail rate of the pattern [1]. Typical laser wavelengths are infrared (1064nm and 1320nm), so they penetrate the substrate of a flip-chip packaged part and interact with active silicon and surrounding contacts. In this paper, we quantify the effect of the laser on the transistor by measuring change in drain current, I_d, with and without laser illumination. We then use the change in I_d to quantify differences in threshold voltage, V_T, mobility, μ, and parasitic bipolar junction transistor (BJT) action [2].

Although infrared lasers are needed for this work, the typical wavelengths chosen have vastly different interactions with the transistor. At 1064nm (hc/λ = 1.17eV), the energy of the laser is slightly above the bandgap of silicon (E_{gap} = 1.12eV) and, hence, creates many electron-hole pairs. In contrast, the 1320nm laser has energy below the silicon bandgap (hc/λ = 0.95eV) and is commonly thought to primarily heat the part [1], [3]. We apply the laser (either 1320nm or 1064nm) through a 100X objective on a Zeiss scanning laser microscope. Historically, in both bulk and PD-SOI transistor systems, the electron-hole pair generating 1064nm laser illumination has enhanced the drive current of the transistor [4], [5] while the below-bandgap 1320nm laser has reduced the drive current by heat-induced mobility reduction. In this paper, we show the dominant effect of the 1064nm laser on an SOI transistor is a dramatic V_T reduction through a laser-induced floating body (FB) effect [6], [7], [8]. Surprisingly, we also find a shift in V_T for the SOI transistor under 1320nm laser illumination due to a small, but significant, laser-induced FB potential. The V_T reduction for the 1320nm light is significant enough to cause a crossover from enhanced transistor drive (I_d) at low voltage to suppressed drive at high voltage.

II. Results and Discussion

In Fig. 1(a), we demonstrate clear enhancement of drain current (Id) for an 80nm floated body PD-SOI transistor with 1064nm laser illumination for all gate voltage, Vg , and drain voltage, Vd . In this test structure, we have the additional ability to tie the body to ground. When the body is tied (TB), additional Id is greatly suppressed (laser on and laser off fall nearly on top of each other, data not shown), indicating that the laser is not inducing a significant amount of additional current through electron-hole creation. Instead, the additional electron-hole pairs create a potential on the floated body, which we call a laser-induced floating body effect. Physically, when the electron-hole-pair-creating 1064nm laser illuminates the body of a FB NMOS (PMOS) transistor, excess electrons (holes) can escape the body through the body-source or body-drain p-n junctions to ground. Since the body is floated, excess holes (electrons) in an NMOS (PMOS) transistor mainly escape through recombination events, a much slower process. Hence, an imbalance in electrons and holes can occur, causing a net positive (negative) body potential for NMOS (PMOS) transistors. The additional laser-induced body potential is measurable and as large as ~ 0.4V at typical 1064nm laser powers. VB is positive (negative) for NMOS (PMOS) transistors, so both N and PMOS transistors are forward body biased, hence enhancing drive for both.

In Fig. 1(b), we show Id as a function of Vg in the linear (low Vd) regime, Vd = 0.1V, with and without 1064nm laser illumination. The numerical derivative dId /dVg (transconductance) of the laser off data is also shown, and a linear extrapolation from a few points surrounding the peak transconductance is used to define VT [9]. Differences in VT can then be quantified by measuring Id with and without laser illumination.

To measure further effects of the laser, in Fig. 1(c), Id as a function of sweeping both Vd and Vg together, Vd = Vg ≡ Vd,g , is measured.Again, when the transistor is illuminated with a 1064nm laser, Id increases over no laser illumination. Because Id varies over several orders of magnitude over our range of Vd,g , it is more useful to plot relative changes in Id , defined as

$$\text{Relative change } (\%^d) = \frac{I_d(P_\lambda, V_{,g}) - I_d(P_0, V_{d,g})}{I_d(P_0, V_{d,g})}, \quad (1)$$

where $I_d(P_0, V_{d,g})$ is always defined at $P_0 = 0\,mW$ (laser off). Laser power P_λ at 1320nm (P_{1320} = 6mW) or 1064nm (P_{1064} =1.6 mW) was set and $V_{d,g}$ was then varied. Positive (negative) relative change corresponds to enhanced (suppressed) I_d with respect to the unilluminated transistor. In Fig. 1(d), the relative change in I_d is shown for both 1064nm and 1320nm laser illumination. The relative change for the 1320nm laser is significantly less than 1064nm laser, so no 1320nm data was displayed in Fig. 1(a,b,c).

Unlike the 1064nm laser, which always enhances I_d, the 1320nm laser has a crossover from enhanced I_d at low $V_{d,g}$ to suppressed I_d at high $V_{d,g}$. Two effects are responsible for the crossover at ≈ 0.8V in Fig. 1(d). First, the 1320nm laser heats the transistor, reducing μ, which reduces $I_{d,sat}$ while simultaneously reducing V_T which increases $I_{d,sat}$. (Both μ and V_T decrease as temperature increases.) Additionally, V_T is further reduced by laser-induced V_B. A crossover then occurs as $V_{d,g}$ increases because the reduction in μ becomes more important than the reduction in V_T.

However, because we have body tie capability, we can disentangle the effect of laser heating from a laser-induced FB effect [10], [11], [12]. We find the crossover for the body-tied configuration to be 0.6V and the effect of the laser is diminished by approximately a factor of 2 compared to body-floated configuration (body-tied data not shown). Fitting the expected form of I_d vs. $V_{d,g}$ [13] allows us to extract a value for change in μ for 1320nm laser illumination. We find a reduction in μ of ≈ 2%, which is consistent with mobility change for a 5− 10°C temperature increase expected from the 1320nm laser[14]. Experimentally, we also find an additional body potential of $\leq 0.1V$ with 1320nm laser illumination, indicating this laser also induces an

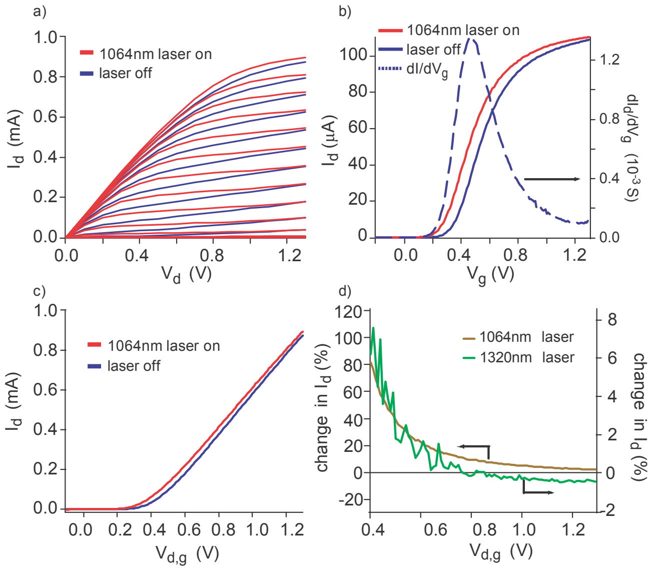


Fig. 1. Laser-induced floating body effect of individual NMOS transistors. All measurements in this figure are made on an 80nm transistor with 1064nm power of 1.6mW or 1320nm power of 6mW. In (a), I_d as a function of V_d is shown for several V_g ranging from $V_g = 0V$ (bottom curve) to $V_g = 1.3V$ (top curve) in $0.1V$ increments. With a 1064nm laser focused on the transistor (red), we demonstrate a clear enhancement of I_d over no laser (blue) due mainly to reduction in V_T (see text). In (b), low V_d measurements ($V_d = 0.1V$) of I_d are shown with 1064nm laser on (red) and off (blue). In order to quantify the reduction in V_T, we analyze the transconductance data (dI_d/dV_g) (dashed curve is an example of laser off dI_d/dV_g), see text. In (c), I_d is measured as a function of $V_{d,g}$ (where $V_{d,g}$ is defined as $V_d = V_g$), again with the 1064nm laser on and off. In (d), the relative change of I_d with the laser (Eq. 1) is shown to elucidate the 1064nm enhancement (enhanced I_d is positive, suppressed I_d is negative relative change). Also shown is the effect of the 1320nm laser on I_d. For a 1320nm laser, there is a crossover at ~ $0.8V$ from enhanced I_d at low $V_{d,g}$ to suppressed I_d at high $V_{d,g}$. Notice also the magnitude of change for the 1320nm laser is at least a factor of ten less than the effect of the 1064nm laser, making it difficult to distinguish from the laser off data and, hence, in (a), (b), and (c) only the 1064nm laser and laser off data are shown.

FB potential. We are currently investigating the mechanism, since a 1320nm laser does not have enough energy to directly create electron hole pairs.

In Fig. 2, we show analysis of data similar to Fig. 1 for FB SOI NMOS transistors of various length and doping. First, we demonstrate the crossover voltage from enhanced (low $V_{d,g}$) to suppressed (high $V_{d,g}$) I_d for the 1320nm laser as a function of doping in Fig. 2(a) and length in Fig. 2(b). A minimum in crossover voltage occurs at medium doping (MVT is medium V_T, LVT is low V_T, and HVT is high V_T). Generation-recombination rates in the body are effected by doping, which could lead to the observed higher crossover voltage.

In Fig. 2(c), V_T reduction is shown for various length and doped transistors with 1320nm laser illumination compared without illumination. The V_T shift is ~ 6% for MVT 80nm NMOS transistor. The V_T reduction for the 1064nm laser, Fig. 2(d), is much larger, ~ 30% for MVT 80nm NMOS transistors.

In Fig. 3, complementary measurements to Fig. 1 and 2 are shown for PMOS transistors. Similar to laser interaction with NMOS transistors, in Fig. 3(a) the 1064nm laser enhances I_d (more negative current). We quantify the $|V_T|$ shift as a function of length and doping in Fig. 3(b) for 1064nm laser illumination. For MVT PMOS

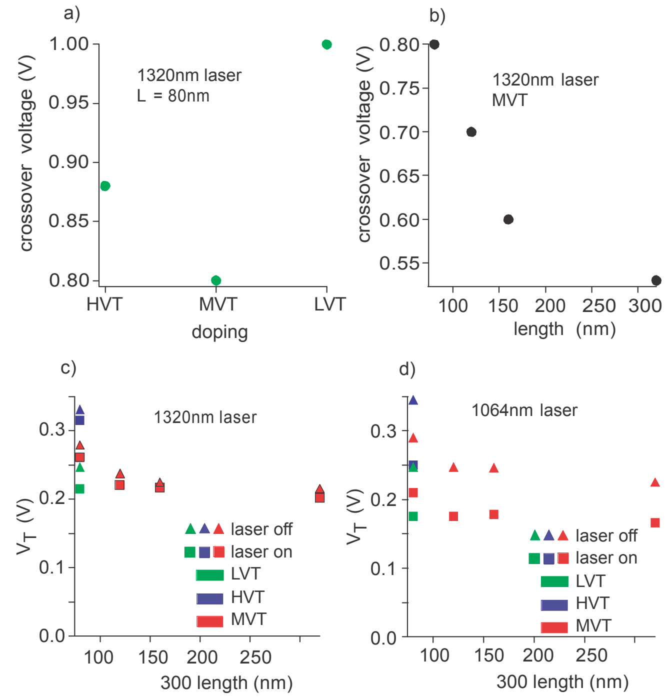


Fig. 2. Parameter analysis of individual NMOS transistors. For a 1320nm laser, at low $V_{d,g}$ the drain current of a transistor, I_d, is enhanced, while at high $V_{d,g}$ the I_d is suppressed, see Fig. 1(d). For (a) and (b), I_d was measured while sweeping $V_{d,g}$ with and without the 1320nm laser illumination (data not shown). In (a), the crossover voltage from enhanced I_d to suppressed I_d is plotted for transistors with three different V_t (see text). The length (L_{drawn}) is 80nm for all three transistors, and L/W ~ 15. In (b), the crossover voltage is plotted as a function of transistor length (L_{drawn}) for four MVT transistors of different lengths (80nm, 120nm, 160nm and 320nm). In (c) and (d), V_T (extracted according to Fig. 1) is plotted for the transistors with either 1320nm or 1064nm laser illumination or no laser illumination. As expected, V_t is always reduced for both the 1064nm and 1320nm lasers. The 1320nm laser reduces V_t by about 6%, while the 1064nm laser reduces V_t by about 30%. The 1064nm laser is found to always enhance I_d, so no crossover exists.

transistors, $|V_T|$ is reduced by ~ 14%, which is considerably less than MVT NMOS transistors (~ 30%). One may also expect a similar reduction in the 1320nm laser interaction with PMOS transistors. In fact, due to noise in the 1320nm V_T measurement (on order of a few %), we are unable quantify the $|V_T|$ reduction other than $\Delta V_T \leq 3\%$.

Although we are unable to quantify the V_T shift for the PMOS transistors, there is still a crossover from enhanced to suppressed I_d for the 1320nm laser. In Fig. 3(c), we show the crossover voltage ($V_{d,g}$ from a plot similar to Fig. 1(d)) as a function of doping. Note this plot looks very similar to the NMOS transistors, Fig. 2(c), where MVT transistors have the smallest crossover voltage. Similarly, there is also a trend for the crossover voltage to increase as the transistor length decreases, Fig. 3(d).

As shown in Figs. 1, 2, and 3, the laser induces a FB effect that reduces V_T. We can emulate the laser-induced body potential in this structure by directly applying a voltage to the body via the body contact. In Fig. 4(a, right), we prepare a circuit with two DC voltage sources, one on the drain and one connected to the body – the body is now tied. In Fig. 4(b) (no laser illumination), we find similar data ($I_d(V_d)$ at several V_g) with a body bias ($V_B = 0.4V$) and no laser illumination as in Fig. 1(a) with laser illumination (1064nm laser) and floated body.

However, the *forward body bias* of the floating body effect will also produce a parasitic current from the intrinsic bipolar junction tran-

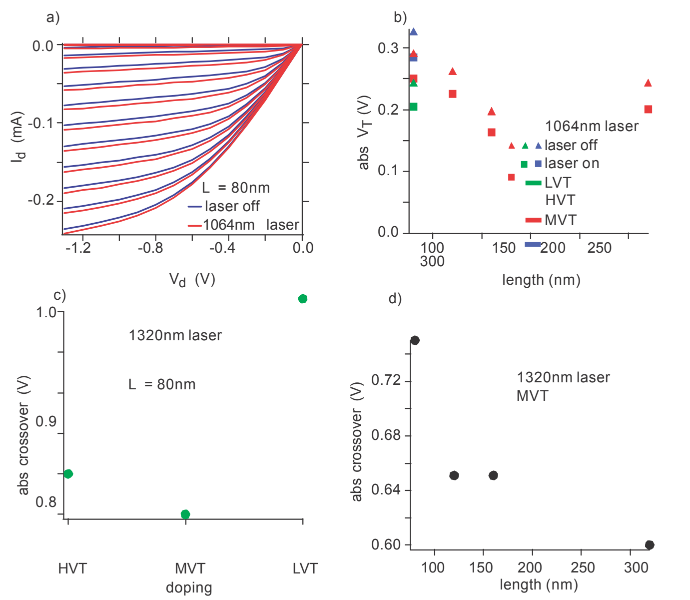
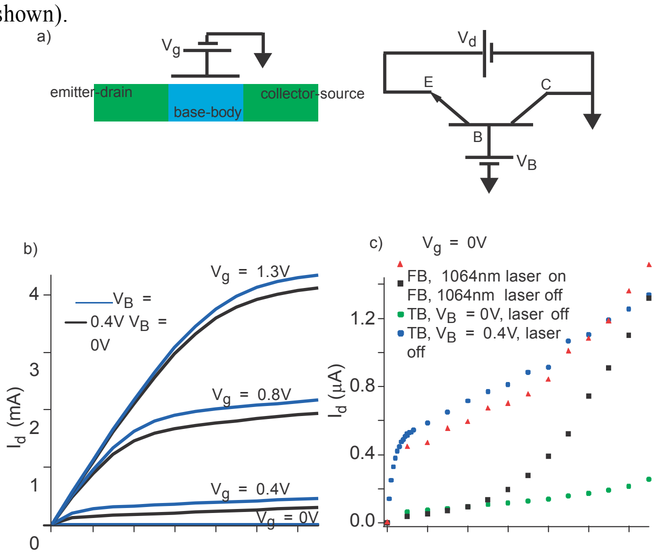


Fig. 3. Parameter analysis of individual PMOS transistors. In (a), I_d as a function of V_d is shown for several V_g ranging from $V_g = 0V$ (top curve) to $V_g = -1.3V$ (bottom curve) in $0.1V$ increments. With a 1064nm laser focused on the transistor (red), we demonstrate a clear enhancement (more current) of I_d over no laser (blue) due mainly to reduction in $|V_T|$ (see text).
Using data similar to Fig. 1(b), in (b) we demonstrate a clear reduction in $|V_T|$ with a 1064nm laser. The reduction of V_T for the PMOS transistor under 1064nm illumination is ~ 14% for all lengths and V_T, as opposed to the ~ 30% change for the NMOS transistors (see Fig. 2). Because the PMOS V_T is less sensitive to the laser than the NMOS, noise in the V_T measurement masks the change of V_T with application of the 1320nm laser. Although we are unable to quantify the change in V_T for the 1320nm laser ($\leq$ 3%), the 1320nm laser still causes a crossover from enhanced I_d at low $V_{d,g}$ to suppressed I_d at high $V_{d,g}$. The crossover voltage is plotted in (c) as a function of doping for an 80nm transistor (MVT = medium, LVT = low, and HVT = high V_T), and also plotted as a function of length for MVT transistors in (d) L = 80nm, 120nm, 160nm, and 320nm.

sistor (BJT) in the MOSFET. In previous floated body studies [15], [16], the body potential, V_B, is not created from a laser. Rather, V_B is induced by keeping the transistor in the off state ($V_g = 0V$) and placing the floated body out of equilibrium by applying a voltage pulse to the source or drain. A transient current then results – the floated body potential turns on the intrinsic bipolar transistor.

In the case of a DC measurement of a laser-illuminated n-FET transistor, the body voltage (V_B) is caused by the laser and thus is not a function of time. (When the laser illuminates the body, the body should come to a steady state potential governed by electron-hole generation by the laser and escape rates (including recombination) of these charge carriers.) I_{BJT} should thus not be a function of time, but we expect I_{BJT} ~ V_B [15], [16]. If we hold $V_g = 0V$, no current should flow through the n-FET except for the parasitic BJT current induced by the laser. Defining the *npn* BJT components (emitter, base, and collector) in terms of the n-FET according to Fig. 4(a), we choose emitter to be the drain ($V_E = V_d$), base to be the body ($V_{base} = V_B$) and collector to be the source ($V_C = V_s$). We then ground the source, so we run the BJT in the common collector situation.

In Fig. 4(c), we compare the off state transistor curves ($V_g = 0V$) so we are in the 'inverted active' regime. Although there is a difference between with and without laser illumination in Fig. 4(c), the difference is very small (~ $10^{-7}A$). Additionally, this small excess current includes both I_{BJT} and the electron-hole pair current caused by the laser. (Surprisingly, the electron-hole current injected by the laser is extremely small, see near $V_d = 0V$.) Notice the change in drive current when $V_g > V_T$ in Fig. 1(a) is ~ mA, so the BJT properties are probably negligible compared to the V_T reduction for the enhanced drive current. The large magnitude of the leakage current in Fig. 4(c) is most likely dominated by the ESD protection diodes on the source and drain. In addition, the TB and FB curves are very similar, indicating the effects of the additional body potential caused either by the laser or by a voltage source are also similar. Also, for both the TB $V_B = 0.4V$ and $V_B = 0V$ case, very little current I_B ~ $10^{-9}A$ travels from the body to source at V_d = 0V(data not shown).



which isolates the physics of the BJT. With the gate grounded ($V_g = 0V$), the main effect of the laser is then the intrinsic BJT turning on because $V_g < V_T$. In Fig. 4(c), we measure I_d (which is also I_s in the *two* terminal geometry) as a function of V_d (in this case, only positive V_d). In terms of the BJT under laser illumination in Fig. 1(a), $V_{BC} > 0$ and $V_{CE} < 0$ when the drain is swept,

0.0 0.2 0.4 0.6 0.8 1.0 1.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2
V_d (V) V_d (V)

Fig. 4. Laser-induced BJT behavior and effect of applied body bias. (a) The n-MOSFET (green is n-type and blue is p-type Si) is labeled as a BJT. By measuring n-FETs with body contacts, we are able to apply a body bias to mimic the effect of the laser. Using the circuit in (a, right), we apply a body bias V_B and measure I_d as a function of V_d. In (b), normal parameter analysis is shown for a 80nm medium V_T body-tied (TB) transistor with applied $V_B =$
0 and $0.4V$. As expected, the forward body bias, V_{BS}, increases the drive of the transistor. In (c), we compare laser-induced floating-body (FB) effect and tied-body (TB) bias effects at $V_g = 0V$. I_{BJT} dominates the current at
$V_g = 0V$; however, it is small (~ μA) for all conditions. Additionally, the
FB laser on curve has a similar magnitude to the TB $V_B = 0.4V$ curve, as expected.

III. Conclusion

In this paper, we have quantified changes in transistor parameters μ, V_T, and BJT action due to 1064nm and 1320nm laser illumination. We find a laser-induced floating body effect reduces V_T for both N and PMOS transistors. For the 1064nm laser, V_T reduction dominates and I_d is enhanced for all V_d and V_g. However, there is a crossover from enhanced to suppressed behavior with the 1320nm laser for both N and PMOS transistors. The crossover, due to simultaneous reduction in μ and V_T, occurs around 0.8V, but is dependent on transistor length and doping.

References

[1] M. Bruce, V. Bruce, D. Eppes, J. Wilcox, E. Cole, and P. Tangyuny- ong. Soft defect localization (SDL) on ICs. *Proc. 28th International Symposium for Testing and Failure Analysis*, pages 21–27, 2002.

ACKNOWLEDGMENT

Sandia is a multiprogram laboratory operated by Sandia Corporation, Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

[2] S.E. Kerns, L.W. Massengill, Jr. Kerns, D.V., M.L. Alles, T.W. Houston, H. Lu, and L.R. Hite. Model for cmos/soi single-event vulnerability. *Nuclear Science, IEEE Transactions on*, 36(6):2305–2310, Dec 1989.

[3] J.A. Rowlette and T.M. Eiles. Critical timing analysis in microprocessors using near-ir laser assisted device alteration (LADA). *Proc. ITC 2003*, pages 264–273, 2003.

[4] W. Zhang, M. Chan, and P.K. Ko. Performance of the floating gate/body tied NMOSFET photodetector on SOI substrate. *IEEE Transactions on Electron Devices*, pages 1375–1384, 2000.

[5] K.S. Shin, K.K. Paek, J.H. Park, T.S. Kim, B.K. Ju, and J.Y. Kang. Parasitic bipolar junction transistors in a floating-gate MOSFET for fluorescence detection. *IEEE Electron Device Letters*, pages 581–583, 2007.

[6] S.M. Sze. *Physics of Semiconductor Devices*. John Wiley and Sons, second edition, 1981.

[7] R.A. Schiebel, T.W. Houston, R. Rajgopal, K. Joyner, J.G. Fossum, Dongwook Suh, and S. Krishnan. A study of floating-body effects on inverter chain delay. *SOI Conference, 1995. Proceedings., 1995 IEEE International*, pages 125–126, 3-5 Oct 1995.

[8] J. Gautier, M.M. Pelella, and J.G. Fossum. Soi floating-body, device and circuit issues. *Electron Devices Meeting, 1997. Technical Digest., International*, pages 407–410, 7-10 Dec 1997.

[9] D.K. Schroder. *Semiconductor Material and Device Characterization*. John Wiley and Sons, second edition, 1998.

[10] J.R. Schwank, M.R. Shaneyfelt, B.L. Draper, and P.E. Dodd. Busfet-a radiation-hardened soi transistor. *Nuclear Science, IEEE Transactions on*, 46(6):1809–1816, Dec 1999.

[11] L.R. Hite, H. Lu, T.W. Houston, D.S. Hurta, and W.E. Bailey. An seu resistant 256 k soi sram. *Nuclear Science, IEEE Transactions on*, 39(6):2121–2125, Dec 1992.

[12] P.E. Dodd, M.R. Shaneyfelt, D.S. Walsh, J.R. Schwank, G.L. Hash, R.A. Loemker, B.L. Draper, and P.S. Winokur. Single-event upset and snapback in silicon-on-insulator devices and integrated circuits. *Nuclear Science, IEEE Transactions on*, 47(6):2165–2174, Dec 2000.

[13] We estimate mobility change from a two parameter best fit to the drain current in saturation, $I_d = A(V_g - V_T)^\alpha$, where A is proportional to μ and α is a scaling factor which depends on channel length, $1 \leq \alpha \leq 2$. V_T is fixed and the A and α are the fit parameters. This method is not nearly as quantitative as measuring I_d and Q_n (charge in the channel measured by C-V characteristics) at low V_d.

[14] S. Im, K. Banerjee, and K. E. Goodson. Modeling and analysis of via hot spots and implications for ULSI interconnect reliability. *IEEE International Reliability Physics Symposium Proceedings*, pages 336 – 345, 2002.

[15] C. Leroux, J. Gautier, A.J. Auberton-Herve, B. Giffard, and M. Spalanzani. Parasitic transients induced by floating substrate effect and bipolar transistor on SOI technologies. *Microelectronic Engineering*, 15:199, 1991.

[16] M. M. Pelella, J. G. Fossum, D. Suh, S. Krishnan, K. A. Jenkins, and M. Hargrove. Low-voltage transient bipolar effect induced by dynamic floating-body charging in scaled PD/SOI MOSFETs. *IEEE Electron Device Letters*, 17:196, 1996.