**RC24490 (W0802-033) February 6, 2008**
**Electrical Engineering**

# IBM Research Report

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# Shockley-Read-Hall Mechanism for Dark Current in Ge-on-SOI Lateral PIN Photodetectors

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## ABSTRACT

The dark current in Ge-on-SOI based photodetectors is analyzed using temperature-dependent current-voltage measurements. Detectors with 10 μm x 10 μm area, and finger spacing of 1.1 μm had dark current that increased from 12 nA at room temperature to 138 nA at 86 °C and -0.5 V applied bias. The activation energy for the reverse leakage current was found to be 0.3-0.35 eV, while ideality factors between 1.4 and 1.8 were determined for the forward leakage current. The results indicate that the reserve and forward dark current in these devices is dominated by Shockley-Read-Hall generation and recombination, respectively.

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Germanium photodetectors have tremendous potential for a number of optical communication applications, including low-cost components for data- and telecommunications, and integrated optical interconnects in high-performance servers [1]-[2]. Ge has a direct band gap of 0.80 eV and an indirect gap of 0.66 eV, making it an excellent absorber in the near infrared. For instance, at a wavelength, $\lambda$, of 850 nm, Ge has an absorption length less than 300 nm, approximately 50 times lower than Si. Ge is also an efficient absorber between $\lambda$ = 1.1 μm and 1.6 μm, where Si is transparent. We have demonstrated lateral p-i-n Ge-on-SOI photodetectors with high performance at low operating voltages [3]-[4], and several groups have also made demonstrations of high-performance Ge detectors on Si and SOI, both in normal incidence [5] and waveguide configurations [6]-[8]. More recently, receivers combining Ge detectors with CMOS ICs have been reported showing excellent sensitivity at data rates in the 10-20 Gbit/sec range [9]-[11].

Despite these performance demonstrations, a main outstanding concern for the viability of Ge detectors as a production technology is the issue of dark current. Dark current is a concern with Ge detectors for two main reasons: the small band gap of Ge relative to Si, and the high number of defects ($\sim 10^8$ cm$^{-2}$) formed when Ge is grown directly on Si or SOI [12]. A comprehensive understanding of the dark current mechanism is particularly important if large-area detectors are needed, or if the Ge detectors need to operate at elevated temperatures. In addition, excess dark current is a major concern for devices with internal gain, such as Ge avalanche photodiodes [13], and low-speed applications, such as infrared sensor arrays [14]. In this paper, we describe the temperature dependence of the dark current in Ge-on-SOI lateral p-i-n photodiodes, and we show that $I_{\mathrm{dark}}$ is dominated by a Shockley-Read-Hall (SRH) trap-assisted generation and recombination mechanism [15].

The Ge-on-SOI detectors utilized for this work are described in [3], and utilize a lateral p-i-n geometry where the spacing, $S$, between adjacent p- and n-implanted regions, is 1.1 μm. These devices were wirebonded to a standard TO5 header and loaded into a windowless closed-cycle Helium cryostat. DC current-voltage measurements were then performed at various fixed temperatures utilizing an HP4145B semiconductor parameter analyzer.

Fig. 1 shows a plot of the dark current, $I_{\mathrm{dark}}$, vs. applied bias voltage, $V_{\mathrm{a}}$, for temperatures ranging from 179 K (-94°C) to 359 K (86°C). The bias voltage was swept from -2 V to +0.3 V. The figure shows that $I_{\mathrm{dark}}$ has a well-behaved bias and temperature dependence in the entire temperature range under investigation. Between 24 $^{\mathrm{o}}$C and 86°C, $I_{\mathrm{dark}}$ at $V_{\mathrm{a}}$ = -0.5 V (-2.0 V) is found to increase by roughly an order of magnitude, from 12 nA (21 nA) to 138 nA (192 nA).

In order to gain additional insight into the leakage mechanism for the Ge p-i-n detectors, an activation energy analysis of the dark current has been performed. For this analysis, $I_{\mathrm{dark}}$ can be assumed to take one of two functional forms:

$$I_{dark} = AT^{3} e^{-E_a/kT} (e^{qV_a/kT} - 1)\,, \tag{1a}$$

or

$$I_{dark} = BT^{3/2} e^{-E_a/kT} (e^{qV_a/2kT} - 1)\,. \tag{1b}$$

If the dark current is dominated by band-to-band generation, then (1a) applies and the activation energy, $E_{\mathrm{a}}$, should be equal to the band gap, $E_{\mathrm{g}}$. However, if $I_{\mathrm{dark}}$ is dominated by trap-assisted generation in the depletion region, the familiar Shockley-Read-Hall (SRH) mechanism [15], then the leakage is described by (1b) where $E_{\mathrm{a}} = E_{\mathrm{g}}/2$ . Accordingly, a semi-log plot of $I_{\mathrm{dark}}$ at a fixed reverse bias (divided by the appropriate prefactor) vs. $1/kT$ should yield a straight line with a slope corresponding to $E_{\mathrm{a}}$. In this way, the dominant dark current mechanism can be determined.

Fig. 2 shows an activation energy plot for the detectors described above at fixed applied bias voltages of $V_{\mathrm{a}}$ = -0.5 V and -2.0 V. At $V_{\mathrm{a}}$ = -0.5 V, the extracted value of $E_{\mathrm{a}}$

is 0.345 eV. This value is almost exactly half the room-temperature band gap of Ge. From this result we can conclude that SRH electron-hole generation is the dominant dark current mechanism at low values of reverse bias. This result is consistent with expectations for our devices, given the high defect density of ~ $10^8$ cm$^{-2}$ in our Ge-on-SOI layers. Also shown in Fig. 2 are the leakage results at $V_a$ = -2.0 V. The leakage trend displays similar behavior to the -0.5-V data at high temperatures, but deviates from the expected exponential behavior at low temperatures. This result is believed to be due to fabrication non-idealities, where portions of the metal fingers overlap onto the intrinsic regions between the $n^+$ and $p^+$ implanted fingers. This overlap causes a parasitic metal-semiconductor-metal device to form, with leakage dominated by field emission, a process that is expected to be nearly temperature independent.

Additional information about the role of traps on the dark current can be determined from the ideality factor, $n$, of the forward bias diode current, $I_f$. By simplifying (1a) and (1b), $I_f$, can be modeled according to

$$I_f \propto e^{qV_a/nkT} , \tag{2}$$

at fixed temperature. In this situation, if the current is driven by carrier diffusion, then $n$ should be equal to 1. However, the ideality factor is expected to increase as the SRH recombination increases, eventually approaching $n = 2$ when the current is completely dominated by trap-assisted recombination [15].

A summary of the above analysis is shown in Fig. 3. In this figure, $\ln(I_f)$ is plotted vs. $V_a/kT$ at various temperatures, and the ideality factor extracted from the data using (2) is shown for each temperature. The results show that $n$ ranges from 1.84 at 179 K to 1.38 at 359 K, providing further confirmation that trapping effects have a significant impact on the transport in our detectors. The temperature dependence of $n$ is likely due to the different prefactors in (1a) and (1b). For band-to-band recombination, the prefactor increases as $T^3$, whereas for SRH recombination, the prefactor goes as $T^{3/2}$. Therefore, increasing temperature tends to favor the band-to-band process, moving $n$ closer to 1.

The results of the analysis presented in this paper are important because they suggest that further reduction in the dark current should be possible if the dislocation density can be reduced. This conclusion is based upon the assumption that the dislocations caused by the direct growth of Ge on SOI are responsible for the observed excess carrier generation and recombination. This is a good assumption given that many previous studies have shown a direct link between dislocations and p-n junction leakage, including recent work where pn-junction leakage in SiGe relaxed buffer layers was shown to scale linearly with threading dislocation density [16]. Of course, further leakage studies are needed, utilizing different device geometries and epitaxial methods, to confirm the primary trapping centers responsible for dark current in detectors made from Ge-on-Si and Ge-on-SOI layers.

In conclusion, the dark current in Ge-on-SOI lateral p-i-n photodiodes has been investigated as a function of temperature. The reverse-bias dark current increases roughly 10x from 25 °C to 85 °C, and modeling shows a strongly-trap-related leakage mechanism both in forward and reverse bias. This study should be helpful for further optimization of Ge-based detectors both for high-speed datacomm receivers and for other applications where sensitivity to dark current is likely to be very important.

The authors would like to acknowledge the partial support of DARPA under contract MDA972-03-3-0004.

# References

[1] J. Kash, C. Baks, S. Gowda, L. Graham, A. Hajimiri, C. Haymes, J. Jewell, D. Kucharski, D. Kuchta, Y. Kwark, P. Pepeljugoski, J. Schaub, C. Schuster, and J. Tiemo, “Bringing optics inside the box: recent progress and future trends,” 16th Annual Meeting of the IEEE Lasers & Electro-Optics Society (LEOS), Tucson, AZ, Oct. 26-30, 2003.

[2] C. Gunn, “CMOS photonics,” 2nd International Conference on Group-IV Photonics, Antwerp, Belgium, Sep. 21-23, 2005.

[3] G. Dehlinger, S. J. Koester, J. D. Schaub, J. O. Chu, Q. C. Ouyang, and A. Grill, “High-speed germanium-on-SOI lateral PIN photodiodes” *IEEE Phot. Technol. Lett.* **16**, 2547 (2004).

[4] S. J. Koester, J. D. Schaub, G. Dehlinger, and J. O. Chu, “Ge-on-SOI infrared detectors for integrated photonic applications,” *IEEE J. Sel. Top. Quant. Electron*. **12**, 1489 (2006).

[5] M. Jutzi, M. Berroth, G. Wöhl, M. Oehme, and E. Kasper, “Ge-on-Si vertical incidence photodiodes with 39-GHz bandwidth,” *IEEE Phot. Technol. Lett.* **17**, 1510 (2005).

[6] D. Ahn, C.-Y. Hong, J. Liu, M. Beals, J. Chen, F. X. Kaertner, L. C. Kimerling, and J. Michel, “Ge photodetectors integrated with waveguides for electronic-photonic integrated circuits on CMOS platform,” 4th International Conference on Group IV Photonics, Tokyo, Japan, Sep. 19-21, 2007.

[7] L. Vivien, M. Rouvière, D. Marris-Morini, J. Mangeney, P. Crozat, E. Cassan, X. Le Roux, S. Laval, L. El Melhaoui, J-F. Damlencourt and J-M. Fédéli, “Germanium photodetector integrated in a silicon-on-insulator microwaveguide,”

4th International Conference on Group-IV Photonics, Tokyo, Japan, Sep. 19-21, 2007.

[8] T. Yin, R. Cohen, M. M. Morse, G. Sarid, Y. Chetrit, D. Rubin, and M. J. Paniccia, "31GHz Ge n-i-p waveguide photodetectors on silicon-on-insulator substrate," 4th International Conference on Group-IV Photonics, Tokyo, Japan, Sep. 19-21, 2007.

[9] C. L. Schow, L. Schares, S. J. Koester, G. Dehlinger, R. John, and F. E. Doany, "A 15-Gb/s, 2.4 V optical receiver using a Ge-on-SOI photodiode and a CMOS IC," *IEEE Phot. Tech. Lett.* **18**, 1981 (2006).

[10] S. J. Koester, C. L. Schow, L. Schares, G. Dehlinger, J. D. Schaub, F. E. Doany, and R. A. John, "Ge-on-SOI-detector / Si-CMOS-amplifier receivers for high-performance optical communications applications," *IEEE J. Lightwave Tech.* **25**, 46 (2007).

[11] G. Masini, G. Capellini, J. Witzens and C. Gunn, "A 1550nm, 10Gbps monolithic optical receiver in 130nm CMOS with integrated Ge waveguide photodetector," 4th International Conference on Group-IV Photonics, Tokyo, Japan, Sep. 19-21, 2007.

[12] H.-C. Luan, D. R. Lim, K. K. Lee, K. M. Chen, J. G. Sandland, K. Wada, and L. C. Kimerling, "High-quality Ge epilayers on Si with low threading-dislocation densities," *Appl. Phys. Lett.* **75**, 2909 (1999).

[13] Y. Kang, S. Litski, G. Sarid, M. Morse, M. J. Paniccia, A. Pauchard, K. G. Gan and J. E. Bowers, "Ge/Si avalanche photodiodes for 1.3μm optical fiber links," 4th International Conference on Group-IV Photonics, Tokyo, Japan, Sep. 19-21, 2007.

[14] L. Colace, G. Masini, S. Cozza, G. Assanto, F. DeNotaristefani, and V. Cencelli, "Near-infrared camera in polycrystalline germanium integrated on

complementary-metal-oxide semiconductor electronics," *Appl. Phys. Lett.* **90**, 011103-1 (2007).

[15] W. Shockley, and T. W. Read, "Statistics of the recombinations of holes and electrons" *Phys. Rev.* **87**, 835 (1952); R. N. Hall, "Electron-hole recombination in germanium" *Phys. Rev.* **87**, 387 (1952).

[16] G. Eneman, E. Simoen, R. Delhougne, P. Verheyen, R. Loo, and K. De Meyer, "Influence of dislocations in strained Si/relaxed SiGe layers on $n^+/p^-$ junctions in a metal-oxide-semiconductor field-effect transistor technology," *Appl. Phys. Lett.* **87**, 192112-1 (2005).

# Figure Captions

Fig. 1. Plot of dark current, $I_{\mathrm{dark}}$, vs. applied bias voltage, $V_{\mathrm{a}}$, for a 10 μm x 10 μm Ge-on-SOI photodetector with finger spacing, $S$, of 1.1 μm, at temperatures, $T$, ranging from 179 K to 359 K.

Fig. 2. Plot of $\ln(I_{\mathrm{dark}}/T^{3/2})$ vs. $1/kT$ for same device as in Fig. 1 at $V_{\mathrm{a}} = -0.5$ V and -2.0 V. The extracted activation energy, $E_{\mathrm{a}}$, is 0.345 eV at $V_{\mathrm{a}} = -0.5$ V.

Fig. 3. Plot of $\ln(I_{\mathrm{f}})$ vs. $V_{\mathrm{a}}/kT$ for a 10 μm x 10 μm detector with $S = 1.1$ μm at various temperatures. The ideality factor, $n$, ranges between 1.38 at $T =$ 359 K to 1.84 at $T = 179$ K.

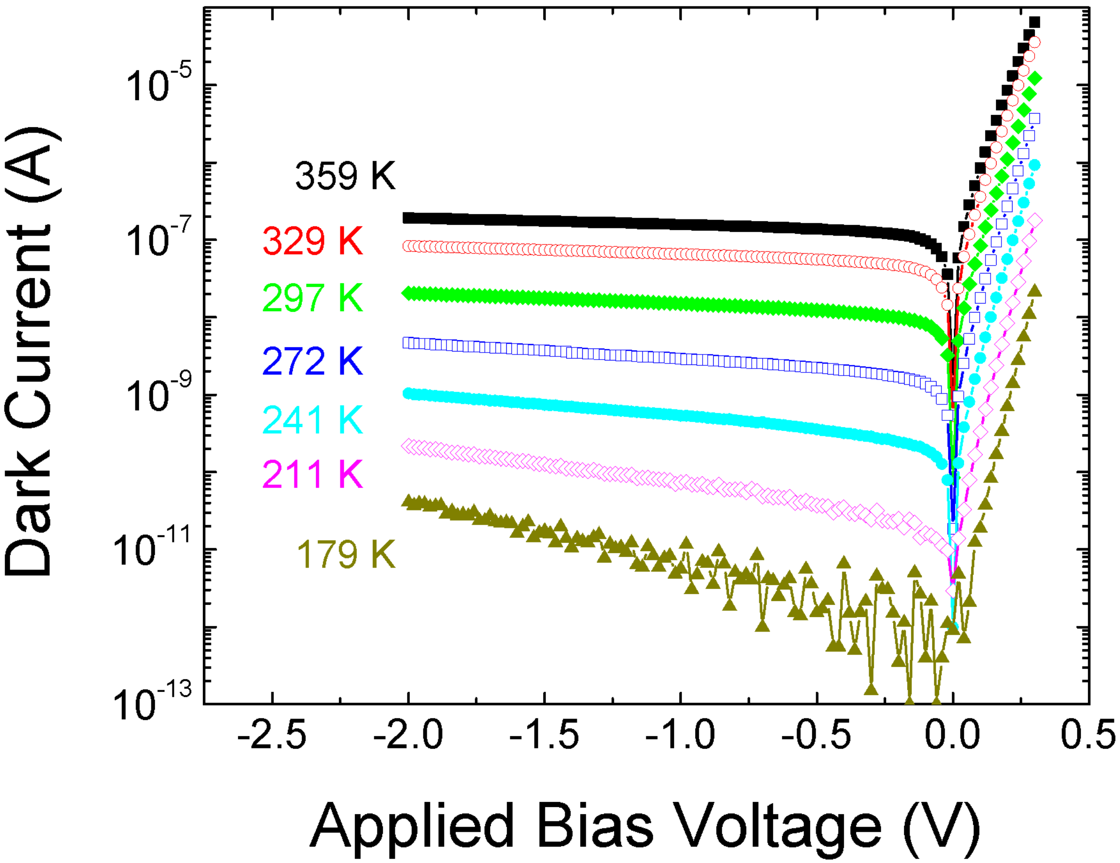

Fig. 1. S. J. Koester *et al.*, *Appl. Phys. Lett.*

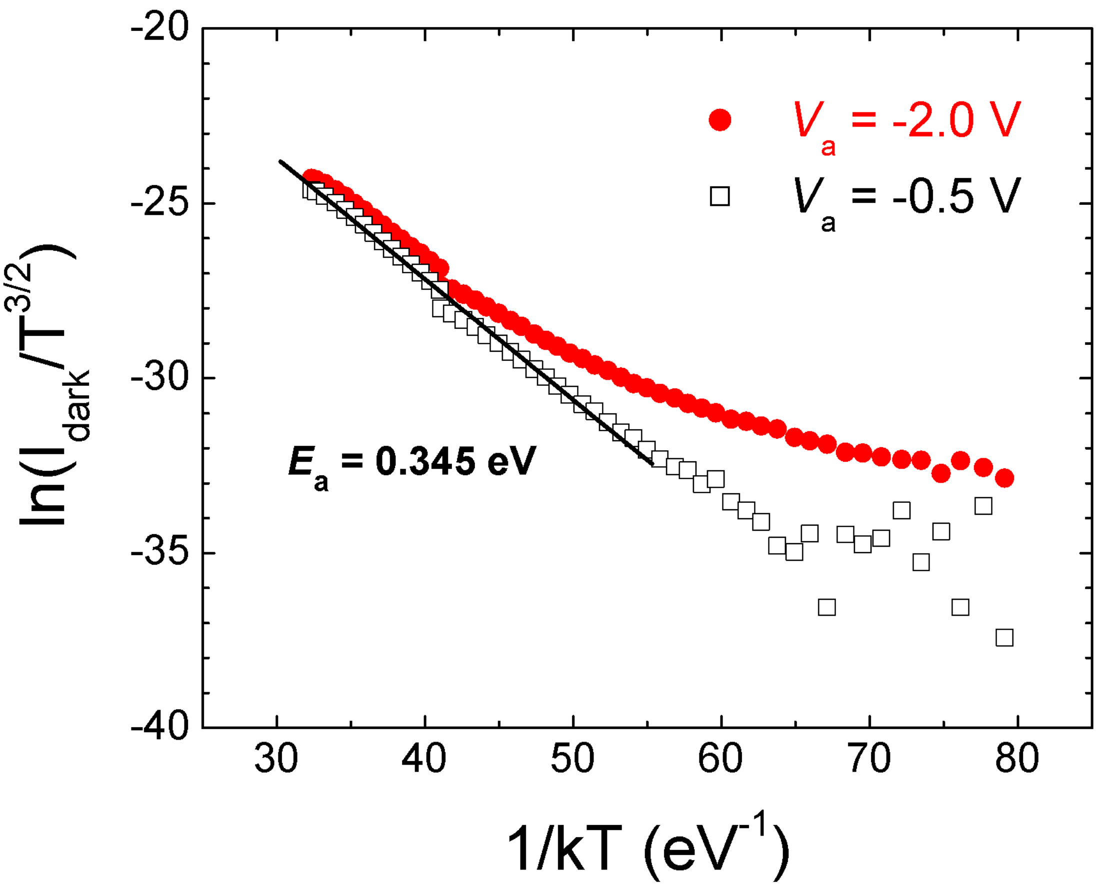

Fig. 2. S. J. Koester *et al*., *Appl. Phys. Lett.*

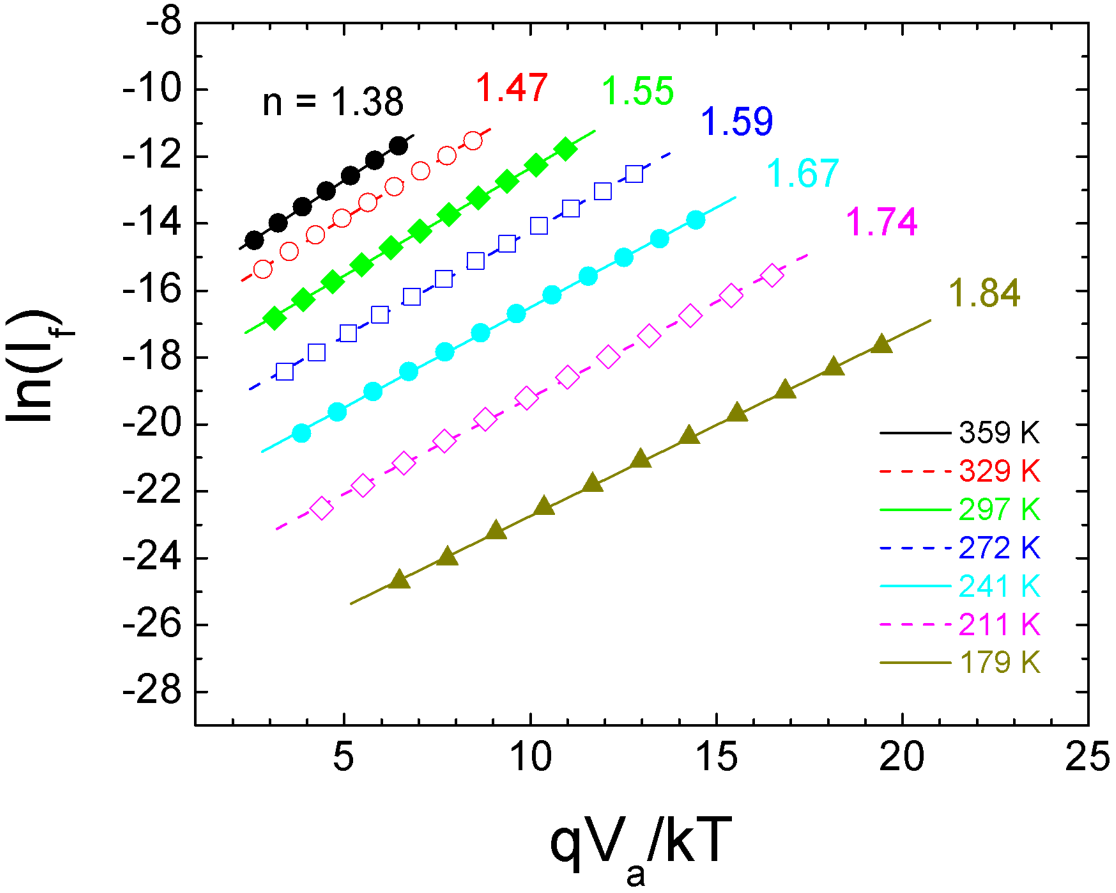

Fig. 3. S. J. Koester *et al.*, *Appl. Phys. Lett.*