The Power Conversion Efficiency of Visible Light Emitting Devices in Standard BiCMOS Processes

P.I. Kuindersma(1), T. Hoang(2), J. Schmitz(2), M.N. Vijayaraghavan(1), M. Dijkstra(3), W. van Noort(4), T. Vanhoucke(1), W.C.M. Peters(5), M.C.J.C.M. Kramer(1)

(1)NXP-TSMC Research Center, Kapeldreef 75, 3001 Leuven, Belgium
(2) MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
(3)NXP Semiconductors IC Design Lab, Eindhoven, The Netherlands
(4)NXP Semiconductors, Fishkill, NY, USA
(5)NXP Semiconductors Nijmegen, The Netherlands
E-mail: piet.kuindersma@nxp.com

***Abstract* — We present experimental and theoretical proof for a single and unique relationship between the breakdown voltage and power efficiency of visible light emitting devices fabricated in standard BiCMOS processes.**

I. INTRODUCTION

Electrically stimulated light emission from silicon is potentially of great importance for a number of applications, e.g. in various domains of (remote) optical or bio-optical sensing. In these domains it is highly attractive to generate the optical stimulus and the subsequent opto-electronic response by the very same silicon chip. This silicon optical sensor chip then basically acts as a transceiver: it consists of a light generating and detecting function, with integrated associated functionality.

Regarding the light generation, an important question is: what is the electrical-to-optical power conversion efficiency ? The optical power useful in applications is of course the power delivered in a specified external numerical aperture (NA), and also in a specified wavelength range. We focus on the visible component of the emission by reverse biased p-n junctions in breakdown [1-3]. The advantage of the visible range is at the receiver side, as silicon photodiodes have good quantum efficiency.

Measuring, modeling and assessing the power conversion efficiency, from electrical input power to useful optical output power is the goal of the present work. As a result we found a single and unique relationship, valid for all architectures, between the conversion efficiency and the actual breakdown voltage.

II. DEVICES AND EXPERIMENTS

All devices are realized in standard BiCMOS process technologies [4], without any process modifications, in production lines of NXP Semiconductors. The investigated structures are diodes (see Fig. 1) and bipolar transistors operated in various electrical driving modes. All devices have an optical window to allow light emission. Breakdown voltages range from 2.9 to 14.1 V, depending on device type and driving mode. Small and large, single and multiple spot devices have been investigated.

We have measured the output power-versus-current (PI) characteristics in the visible (VIS), i.e. $\lambda < 780$nm, and infra red (IR) ranges separately. The high sensitivity of silicon photodiodes in the VIS range is very attractive for optical applications. Therefore, in this work we focus on light emission in that range. For all structures we have measured that the visible optical output power is typically about 1/3 of the total optical output power. This corresponds to a spectral efficiency loss of -5 dB.

Upon switching a transistor from one driving mode to another, the breakdown voltage and power efficiency change. In addition the optical spot may change as well, especially for larger spots. As an example for an npn transistor, the change in optical spot upon switching from negative to positive emitter-base voltage (V_{EB}), is demonstrated in Fig. 2. The corresponding PI characteristics of the npn transistor are presented in Fig. 3. For the diode of Fig. 1, the PI characteristic is shown in Fig. 4.

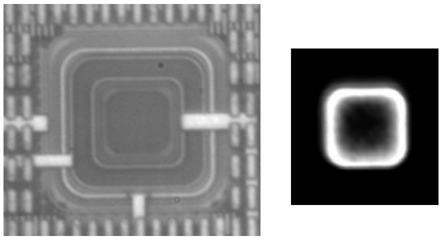

Figure 1 Example of a standard BiCMOS light emitting device with an optical window. Shown are a microscope top-view image and a recorded visible emission pattern.

978-1-4244-1768-1/08/$25.00©2008 IEEE

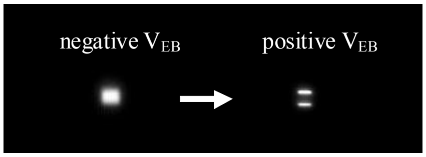

Figure 2 Change in the shape of the visible optical spot of an npn transistor, with a 7x7μm^2 optical window, upon switching the driving mode.

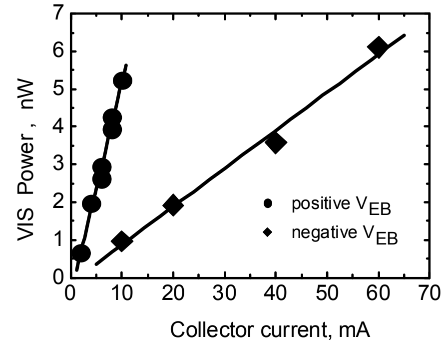

Figure 3 PI characteristic measured in the VIS range in an NA = 0.4, for an npn transistor, in two driving modes.

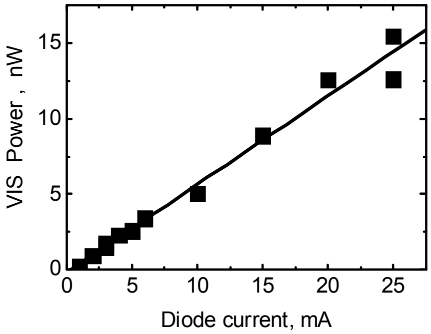

Figure 4 PI characteristic for a p$^+$n diode measured in the VIS range in an NA = 0.4.

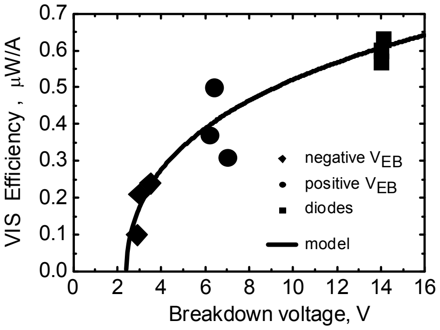

Figure 5 Efficiency (dP/dI) as a function of the breakdown voltage (measured in an NA = 0.4). The individual measurement points for each driving mode represent a different device architecture. The continuous line represents the derived model.

Common to all investigated device types and driving modes, we found a strictly linear relationship between the optical output power (P) and electrical current (I). Moreover the measurements showed that there is a single and unique relationship between the efficiency (dP/dI, in units of W/A) and the actual breakdown voltage (V_{BD}). Experimentally, the relationship holds for all tested device types (diodes and transistors) and driving modes as is shown in Fig. 5

III. ELECTRO-OPTICAL CONVERSION MODEL

We derived a physical model, which describes the non-linear relationship between dP_{VIS}/dI and V_{BD} very well, and in simple terms. All measured VIS data are in good agreement with the derived theoretical relationship given by

$$\frac{dP_{VIS}}{dI} = A\sqrt{\sqrt{V_{BD}} - \sqrt{V_{THR}}}\,, \tag{1}$$

with $A = 0.41\times10^{-6}\,(V)^{0.75}$ and $V_{THR} = 2.4$ V being constants. Plotting the square of the light emission efficiency, $(dP_{VIS}/dI)^2$, versus $(V_{BD})^{0.5}$, as shown in Fig. 6, yields indeed a straight line. The cut-off at $V_{BD} = V_{THR}$ is the threshold for light emission.

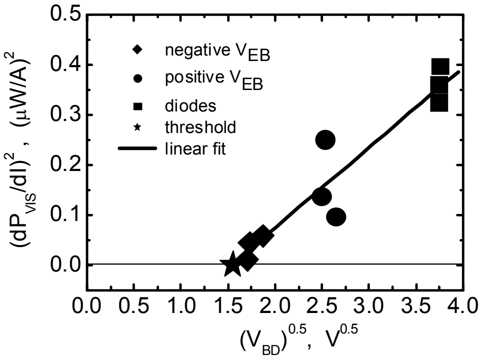

Figure 6 $(dP_{VIS}/dI)^2$ as a function of $(V_{BD})^{0.5}$. The individual measurement points for each driving mode represent a different device architecture.

IV. INSERTION LOSSES

All optical powers were measured with microscope objectives with an NA of 0.4. This limited NA, together with the strong refraction at the Si-air, and Si-SiO_2 interface, leads to a very high insertion loss between the light source inside the silicon and the entrance of the measurement system. The combined effect, of external NA and the strong refraction, yields a transmission, T, given by

$$T = \frac{1}{2}\left[1-\sqrt{1-\left(\frac{n_{air}}{n_{Si}}\right)^2 NA^2}\right], \tag{2}$$

with $n_{air} = 1$ and $n_{Si} = 3.5$. Using Eq. (1) we can calculate that the insertion loss is -25dB. Simple calculation shows that the additional losses due to reflections in the silicon back-end are -1.5 dB. Shielding and absorption losses are estimated to be -0.5 dB. Hence, the total insertion loss equals -27 dB.

V. POWER CONVERSION EFFICIENCY

Measured optical output powers (in dBm, in NA = 0.4) as a function of the electrical input powers (also in dBm) for all devices, are presented in Fig. 7. For reference, lines of constant power conversion efficiency (in dB) are shown as thick solid lines in this plot.

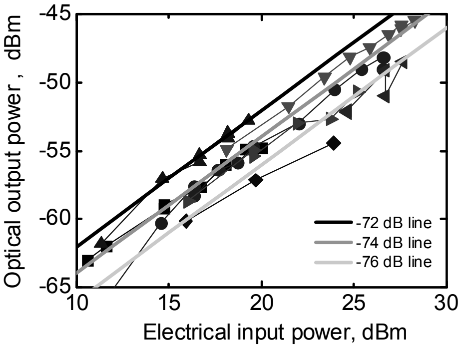

Figure 7 Optical output power measured in an NA = 0.4 as a function of electrical input power. The thick lines are for reference.

The theoretical power conversion efficiency in the VIS range, $\eta_{\text{POWER, VIS}}$ (in units W/W) can be derived from Eq. (2) and is given by

$$\eta_{POWER,VIS} = \frac{A\sqrt{\sqrt{V_{BD}}-\sqrt{V_{THR}}}}{V_{BD}+V_{SERIES}}, \qquad (3)$$

where V_{SERIES} is the voltage drop over the ohmic series resistance of the device. Comparison of theory and experiments for the VIS measurements, again using $A = 0.41\times10^{-6}\,(V)^{0.75}$ and $V_{THR} = 2.4$ V, is shown in Fig 8. Above the threshold voltage, V_{THR}, the power conversion efficiency is only weakly dependent on the actual value of the breakdown voltage. There is a maximum as function of the breakdown voltage, which follows from the condition

$$\frac{d\eta_{POWER,VIS}}{dV_{BD}} = 0. \qquad (4)$$

Using series expansion $V_{BD,max}$ is given by

$$V_{BD,\max} = \frac{16}{9}V_{THR} + 2V_{SERIES}. \qquad (5)$$

For our devices, $V_{BD,max}$ is typically around 5 V.

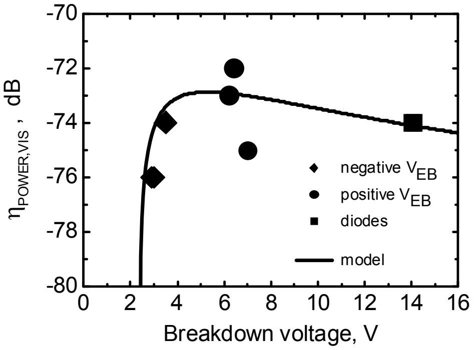

Figure 8 VIS power conversion efficiency (NA = 0.4), as a function of the breakdown voltage. The individual measurement points for each driving mode represent a different device architecture.

With an NA = 0.4 of the measurement system, the maximum VIS power conversion efficiency was measured to be -72 dB. This number consists of the following three contributions: -40 dB power conversion efficiency in the silicon, -27 dB total insertion loss, from the light spot inside the silicon to the entrance (NA = 0.4) of the measurement system, and -5 dB for the VIS fraction of the total spectrum.

VI. CONCLUSIONS

The power conversion efficiency (in W/W), from electrical input power to useful VIS optical output power, was measured, modeled and assessed, for a variety of standard BiCMOS devices.

We found a single and unique relationship, valid for all architectures, between the power conversion efficiency and the actual breakdown voltage.

ACKNOWLEDGMENTS

One author (T. Hoang) was supported by the Dutch Technology Foundation STW under project nr. 6159.

REFERENCES

[1] R. Newman, Physical Review, Vol. 100, No. 2, 1955, pp. 700-703.
[2] A. L. Lacaita *et al.*, IEEE Trans. on Electron Devices, Vol. 40, No. 3, 1993, pp. 577-582.
[3] N. Akil *et al.*, IEEE Trans. Electron Devices, Vol. 46, pp. 1022-1028, May 1999.
[4] W. v.d. Wel *et al.*, IEEE Trans. on Electron Devices, Vol. 43, No. 9, 1996, pp. 1539-1546.