

Photo Carrier Generation in Bipolar Transistors

Johan H. Klootwijk, *Member, IEEE*, Jan W. Slotboom, *Member, IEEE*, M. S. Peter, Victor Zieren, and Dick B. de Mooy

Abstract—Anomalous substrate currents have been observed in bipolar NPN-transistors, dependent on the collector bias, at high current levels. These currents appear to originate from light that is generated in the collector base junction when it is reverse biased. This light generates electron hole pairs in the n^+ buried layer-substrate diode, yielding a considerable substrate current.

This paper will show that these substrate currents can be used as a useful monitor for the occurrence of avalanche multiplication and high-level injection (Kirk effect) in heterojunction bipolar transistors (HBTs).

Index Terms—Avalanche currents, light emission, SiGe HBTs, Silicon devices, Silicon-Germanium.

I. INTRODUCTION

IT IS WELL known that when a p-n-junction is biased into avalanche, light is emitted. This light is absorbed in the surrounding substrate and generates electron-hole pairs [1]–[3]. In this paper, it will be shown that light emitted from the collector–base junction of a bipolar transistor generates a significant substrate current in the underlying buried layer-substrate (n^+ p) diode. We have found that the ratio between the substrate current and the avalanche current (I_{sub}/I_{ava}) is approximately 2×10^{-5} , which is in agreement with what has been measured in MOS transistors [1], [4]. This ratio is independent of the bias of the collector substrate diode. Accordingly, this substrate current can be used as a monitor for the occurrence of avalanche multiplication and high-level injection in the collector base diode. It can therefore be utilized to differentiate between series resistance effects and the Kirk-effect.

II. EXPERIMENTAL

The fabrication process for the SiGe HBTs, used in this investigation, has been described extensively in [5]. By using selective epitaxial growth in an LPCVD reactor the base has been deposited with a Germanium content of 16%. A measured Gummel plot is shown in Fig. 1. In this plot, the collector and base current as well as the substrate current are shown as a function of the base–emitter voltage.

The collector and base current show an ideal exponential behavior (slope ≈ 60 mV/dec). For $V_{be} > 0.8$ V the curves start to deviate from the ideal behavior. This deviation is due to high-

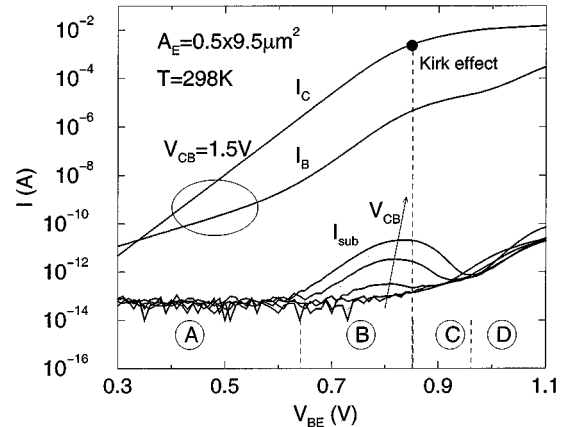


Fig. 1. Gummel plot of a bipolar transistor ($A_E = 0.5 \times 9.5 \mu\text{m}^2$), in which also the substrate current is shown for various V_{cb} (0, 0.5, 1, 1.5, and 2 V).

level injection as well as series resistance effects [5]. It is hard to distinguish between these two effects. The base current shows a kink at high V_{be} . This kink is simply due to a voltage drop across the emitter resistance and a stronger saturation of the collector current (modified Kirk effect) in our SiGe HBTs, as has been extensively described in [6]. In Fig. 1, we observe that a significant substrate current flows for increasing collector base voltages for a specific range of base emitter voltages. This substrate current consists of four parts.

At $V_{be} < 0.62$ V (region A), the measured current is about 60 fA and close to the lowest measurable value (10 fA). Therefore this collector substrate leakage current (I_{sub}) shows no collector base voltage dependence. From medium up to high collector current densities (region B), I_{sub} increases proportionally to the collector current I_C . In addition, I_{sub} increases with increasing collector–base voltage V_{CB} . In regions C and D, base widening (Kirk effect) and emitter series resistance limits the collector current slope. I_{sub} also decreases in region C, but in region D, however, it increases again.

III. DISCUSSION

The observed substrate currents can be explained if we assume that these currents are induced by light that is generated when the collector–base diode is biased into avalanche. This is schematically depicted in Fig. 2.

When the collector–base diode is reverse biased, light is generated, which generates electron hole pairs in the buried layer-substrate diode. This yields a considerable substrate current, implying a direct relation between the avalanche and the substrate current. In order to verify this relation, in Fig. 3 the collector, substrate and avalanche ($I_{ava} = I_B(V_{CB} = 0 \text{ V}) - I_B(V_{CB} = 2 \text{ V})$) current are shown as a function of V_{be} .

Manuscript received April 9, 2002; revised June 13, 2002. The review of this paper was arranged by Editor P. Yang.

J. H. Klootwijk, J. W. Slotboom, V. Zieren, and D. B. de Mooy are with Philips Research Laboratories Eindhoven, The Netherlands (e-mail: johan.klootwijk@philips.com).

M. S. Peter was with Philips Research Laboratories, Eindhoven, The Netherlands. He is now with Texas Instruments, Germany.

Publisher Item Identifier 10.1109/TED.2002.802616.

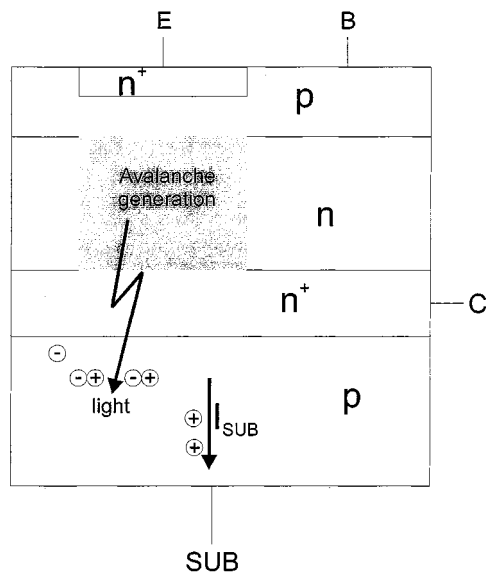


Fig. 2. Schematic view of a bipolar transistor with generation of light due to avalanche.

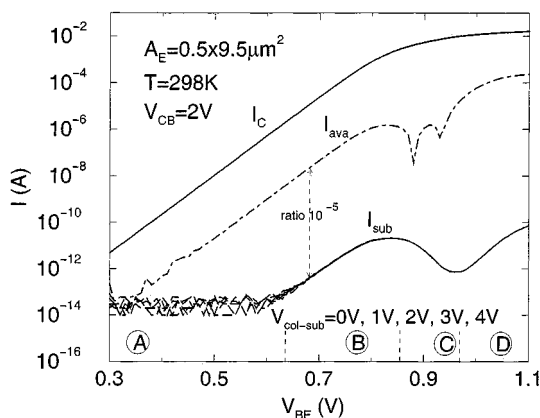


Fig. 3. Collector (I_C), substrate (I_{SUB}), and avalanche current plotted as a function of the base emitter voltage. I_{ava} is obtained by subtracting the base current I_B measured at $V_{CB} = 2$ V from the base current measured at $V_{CB} = 0$ V ($I_{ava} = I_B(V_{CB} = 0 \text{ V}) - I_B(V_{CB} = 2 \text{ V})$). I_{SUB} is plotted for different $V_{col-sub}$, showing no dependence on the collector–substrate voltage.

In Fig. 3, we observe that the avalanche current (I_{ava}) increases monotonously until $V_{be} = 0.88$ V. Then this current decreases for $0.88 \text{ V} < V_{BE} < 0.93$ V. Finally, at $V_{BE} > 0.93$ V the avalanche current increases again. The substrate current shows a similar behavior (see also Fig. 1), independent from the reverse collector–substrate bias ($V_{col-sub}$).

Fig. 4 shows simulation results of the electric field in the collector–base junction, where the electric field is shown at a constant collector–base voltage ($V_{CB} = 2$ V) for three different base–emitter voltages: $V_{BE} = 0.8$ V, $V_{BE} = 0.85$ V and $V_{BE} = 0.9$ V, respectively.

At the onset of the Kirk effect, the electric field of the collector–base junction decreases at the base side, then becomes flat and finally increases at the n^+ buried layer side. As this electric field counts exponentially into the impact ionization, it is obvious that the avalanche current and therefore the substrate current first decreases with increasing base–emitter voltage (region C) and then increases again with increasing electric field

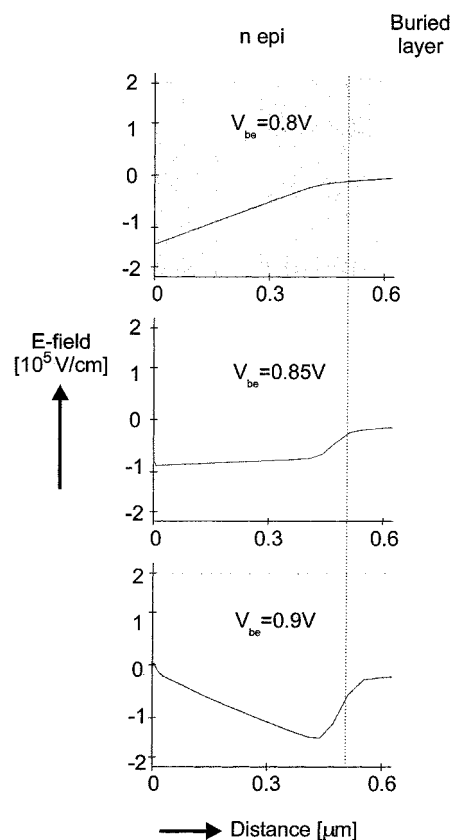


Fig. 4. Electric field at $V_{CB} = 2$ V as a function of the base–emitter voltage V_{BE} : $V_{BE} = 0.8$ V, $V_{BE} = 0.85$ V, and $V_{BE} = 0.9$ V, respectively. The occurrence of avalanche and Kirk effect is clearly observed.

at the buried layer side (region D). So, the substrate current acts like a measure for the behavior of the electric field in the collector–base junction and thus for the occurrence of avalanche and Kirk effect. From Fig. 3, it also appears that the ratio between the substrate current and the avalanche current is approximately 10^{-5} . This value has been reported being a typical value for light generated currents if the detecting diode is placed close the transistor [1], [3].

In addition, Fig. 5 shows that substrate current measurements at different collector currents show the same temperature dependence. The activation energy is $E_A = 60$ meV. This is the same activation energy as the avalanche current of the CB-diode, given by the known negative temperature coefficient of the impact ionization rate [7].

When the parasitic base–collector–substrate p-n-p-transistor is concerned, the substrate current is expected to increase monotonously with increasing “collector–base” voltage, since the electric field will increase monotonously and will not “invert” due to the absence of an p^+ buried layer. This is demonstrated in Fig. 6, where the Gummel plot as well as the substrate current of the parasitic pnp-transistor are shown. It is clearly observed, that the substrate current increases monotonously with increasing substrate voltage (which forms the collector of the p-n-p transistor).

In order to verify whether light is generated when the collector base junction is biased into avalanche, we have performed optical measurements using photon emission microscopy in the

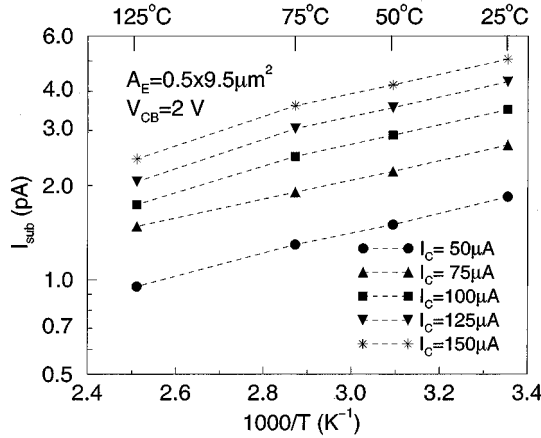


Fig. 5. Substrate current as a function of temperature at various collector currents.

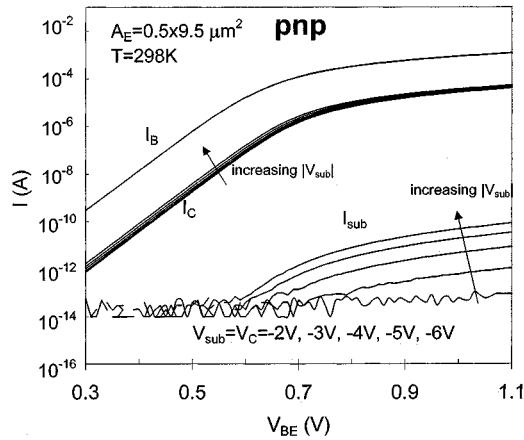


Fig. 6. Measurement of the parasitic base-collector-substrate (p-n-p) transistor. Due to the absence of the p^+ layer, the substrate current increases monotonously with increasing substrate voltage.

400–900 nm wavelength range. Fig. 7 shows a typical photo emission microscopy image. The npn transistor is located in the middle of the bondpads, where a light spot is detected clearly at sufficient high collector base reverse biases. At small collector base reverse biases (V_{CB}) no light was detected, indicating that the light is not generated in the forward biased emitter base junction but is induced by the into avalanche biased collector base junction.

In order to quantify the amount of emitted photons the light intensity has been measured as a function of the collector base voltage (V_{CB}) and collector current ($I_C(V_{EB})$). Fig. 8 shows that the substrate current is proportional to the amount of light that is generated because of avalanche. This proves that the substrate current can indeed be used as a monitor for the occurrence of avalanche and Kirk effect in bipolar transistors and therefore enables to make a distinction between the Kirk effect and emitter series resistance effects.

Although this paper concerns measurement results obtained from bipolar SiGe transistors only, similar results have been obtained on more conventional silicon bipolar transistors.

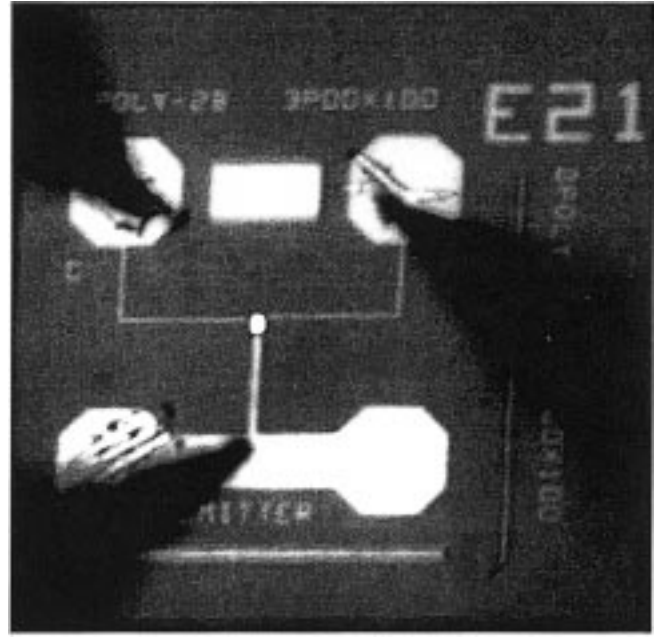


Fig. 7. Photon emission microscopy image of a transistor during measurement. Light is generated due to avalanche of the collector base diode. The transistor was biased at $V_{BE} = 0.82$ V; $V_{CB} = 3$ V; and $V_{CS} = -1$ V.

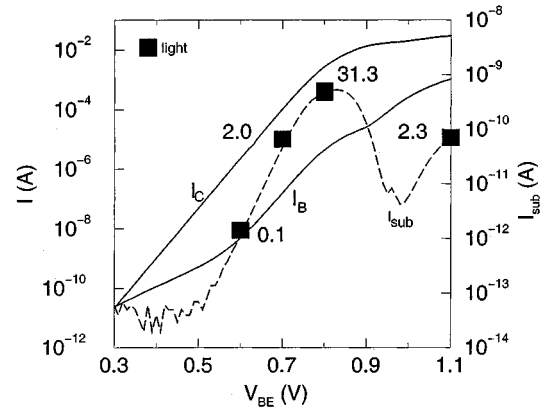


Fig. 8. Light intensity measurement. The base and collector current are drawn in solid lines, the substrate current is drawn in a dashed line. The measured light, generated in the transistor, is depicted by black squares. The numbers in the figures are the intensities (arbitrary scale). The transistor was biased at $V_{CB} = 3$ V; $V_{CS} = -1$ V.

IV. CONCLUSION

We have shown that in heterojunction bipolar transistors (HBTs), photons, emitted from the reverse-biased collector-base junction under high current conditions, generate substrate currents in the n^+ buried layer-(p) substrate diode.

This current can easily be measured and monitors accurately, without interference of emitter or base resistance, how the electric field in the collector-base junction changes with high-level injection (Kirk effect). It can therefore be well utilized to differentiate between series resistance effects and the Kirk-effect.

REFERENCES

- [1] D. Esseni and L. Selmi, "Experimental signature and physical mechanisms of substrate enhanced gate current in MOS devices," in *IEDM Tech. Dig.*, 1998, pp. 579–583.

- [2] N. Akil, S. E. Kerns, D. V. Kerns, A. Hoffmann, and J. P. Charles, "A multimechanism model for photon generation by silicon junction in avalanche breakdown," *IEEE Trans. Electron Devices*, vol. 46, pp. 1022–1028, May 1999.
- [3] H. Ishiuchi, N. Tamba, J. D. Shott, C. J. Knorr, and S. S. Wong, "Hot-electron-induced minority-carrier generation in bipolar junction transistors," *IEEE Electron Device Lett.*, vol. 11, pp. 490–492, Nov. 1990.
- [4] M. Rasras, I. De Wolf, G. Groeseneken, B. Kaczer, R. Degraeve, and H. E. Maes, "Hot-carrier generation as the origin of Fowler–Nordheim-induced substrate hole current in thin oxides," *IEEE Trans. Electron Devices*, vol. 48, pp. 231–238, Feb. 2001.
- [5] M. S. Peter, J. W. Slotboom, and D. Terpstra, "Impact ionization and neutral base recombination in SiGe HBTs," in *Proc. IEEE BCTM 1999*, Minneapolis, MN, 1999, pp. 58–61.
- [6] M. S. Peter, J. W. Slotboom, D. Terpstra, J. H. Klootwijk, F. van Rijs, and W. B. de Boer, "Base current kink effect in SiGe HBTs," in *Proc. 29th Eur. Solid-State Device Research Conf. ESSDERC*, 1999, pp. 716–719.
- [7] W. Maes, K. de Meyer, and R. van Overstraeten, "Impact ionization in silicon: A review and update," *Solid-State Electron.*, vol. 33, no. 6, pp. 705–710, 1990.



Johan H. Klootwijk (S'95–M'98) was born in Hengelo, The Netherlands, on June 2, 1969. He received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Twente, Enschede, The Netherlands, in 1993 and 1997, respectively. His Ph.D. dissertation dealt with the development, characterization, and application of deposited interpoly dielectrics for nonvolatile memories.

In October 1997, he joined the Philips Research Laboratories, Eindhoven, The Netherlands, where he was involved in the development and characterization of Si and SiGe bipolar transistors, SOI/SOA technologies, and reliability of thin dielectrics. His current research activities are on the development of InP based HBTs and InP systems for wideband RF applications.

Dr. Klootwijk received the Best Paper Award for his contribution on the ESSDERC Conference in 2001. He was the Tutorial Chairman of the ICMTS 2002, Cork, Ireland.



Jan W. Slotboom (M'82) was born in Utrecht, The Netherlands, on December 26, 1942. He received the M.Sc. degree in electrical engineering from the Technical University of Delft, Delft, The Netherlands, in 1966, and the Ph.D. degree from the Technical University of Eindhoven, Eindhoven, The Netherlands, in 1977, performing his dissertation on 2-D numerical device simulation of bipolar transistors and pioneering experiments on bandgap-narrowing in heavily-doped silicon.

In 1967, he joined the Philips Research Laboratories, Eindhoven, where he worked on bipolar device modeling, numerical simulation, and experimental silicon device physics. He was involved in the development of CCD memories for video applications and exploratory research of high-density memories. His current research activities are on research of novel silicon devices (e.g., SiGe bipolar transistors), hot-carrier effects, and new memory cells. He has authored and co-authored over 50 papers and holds 14 patents. Since 1994, he has been a Parttime Professor with the Micro Electronics Center (DIMES), Technical University of Delft.

Dr. Slotboom was a member of the Solid-State Devices Subcommittee of the IEDM in 1980, 1983, and 1984, respectively. He was Vice Chairman and Chairman of International Arrangements for Europe of the IEDM. He has served as a Program Subcommittee Member of the IEDM in 1991 and 1992 and of the BCTM'95 Conference. He has been a member of the Technical Program Committee of the ESSDERC for the last six years.



M. S. Peter was born in Osnabrück, Germany, in 1967. He received the B.S. degree in information technology from the University of Osnabrück.

He joined the Semiconductor Group, Philips Research Laboratories, in 1995, where he worked on simulation and characterization of Si/SiGe bipolar transistors. Since autumn 1999, he has been with Texas Instruments, Germany.



Victor Zieren was born in Haarlem, The Netherlands. He received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Technology, Delft, The Netherlands, in 1979 and 1983, respectively.

In 1983, he joined Philips Research Laboratories, Eindhoven, The Netherlands, where he has been involved in research on the physics, design and technology of thin-film magnetic recording heads for digital audio and perpendicular video recording. Since 1994, his research interests include failure-analysis

and diagnostic techniques for VLSI circuits and other electronic devices, and he has been engaged in electro-optical sampling, spectral and backside photon-emission microscopy, sample preparation methods, and thermal imaging. Since 1997, he has Headed the research group on VLSI testing within the Department "Digital Design and Test." He is the author or co-author of about 50 journal and conference papers and holds 12 U.S. patents.

Dr. Zieren was involved in exploring new current-based test techniques for defect detection in deep submicron integrated circuits, for which he received the Honorable Mention Paper Award at the International Test Conference in 1999.



Dick B. de Mooy received the B.Sc. degree in chemical engineering in 1972.

He joined Philips Research Laboratories, Eindhoven, The Netherlands, in 1966. His experience comprises a wide range of topics in applied chemistry, such as gas discharge lamps and the structure and magnetic properties of intermetallic compounds. He is currently involved in methods for failure analysis of electronic circuits. He is the author or co-author of more than 60 journal and conference papers and holds three U.S. patents.