On the Bremsstrahlung Origin of Hot-Carrier-Induced Photons in Silicon Devices

Andrea L. Lacaita, Member, IEEE, Franco Zappa, Stefano Bigliardi, and Manfredo Manfredi

Abstract—In this paper we report the first spectrally resolved absolute measurements of hot-carrier-induced photon emission in silicon. In order to avoid uncertainties in geometrical and physical parameters, we chose the simplest conceivable device: an avalanching p-n junction. We measured a photon emission efficiency of $2.9 \times 10^{-5}$ photons with energy higher than 1.14 eV per carrier crossing the junction, independent of the lattice temperature down to 20 K. On the basis of these results the Bremsstrahlung origin of the hot-carrier-induced light emission is critically reviewed.

I. INTRODUCTION

BREAKDOWN radiation from "red spots," or microplasmas, in silicon p-n junctions was first reported by Newman et al. [1] in 1955 and since then many papers have been devoted to the phenomenon. It is well established that, whenever the hot-carrier regime is attained, light emission occurs on a broad-band spectrum. Notwithstanding many theoretical and experimental efforts, the basic mechanism involved in this radiative emission is still a debated issue. Recently, experimental results on light emission from hot carriers in silicon MOSFET's [2]-[8], GaAs MESFET's [9], and bipolar transistors [10], [11] have been reported and, depending on the semiconductor, different interband and intraband processes have been invoked.

In silicon devices the emission spectrum can be divided in three regions: the region below the bandgap energy, where peaks due to hole radiative transitions occur [5], [6], [12]; the near-band-edge region, where features related to radiative recombination between an electron and a free hole could be resolved on a smooth background [5]-[7]; and the high-energy region, i.e., the visible wavelength range, where photons are believed to come from transitions of hot electrons within the conduction bands [2], [13].

Since the work of Figielski and Torun [13], Bremsstrahlung (i.e., braking radiation) by hot electrons in the Coulomb field of charged impurities has been regarded as the major cause of photon emission in the visible range. Their theory gives a photon emission efficiency in quantitative agreement with the experimental figure quoted in the pioneering work by Chynoweth and McKay [14], namely $7 \times 10^{-9}$ photons emitted in the visible range per electron crossing an avalanching p-n junction.

However, measurements on crosstalk between silicon avalanche photodiodes, performed in our and other laboratories [15]-[17] repeatedly denoted a photon emission efficiency orders of magnitude higher than the above value. Very recently, Wong reported that the intensity of secondary photon emission in a silicon n-MOSFET does not change if the high-field region is shifted by an auxiliary gate from the drain end to the channel [8]. This result raises serious doubts over the physics underlying the emission. In fact, the impurity density in the channel is at least two orders of magnitude lower than in the drain. Therefore, an impurity-related photon emission should have been reduced by the same figure.

Explaining these puzzling discrepancies is not only a basic physical problem: it is also important for designing devices with improved performance. Hot carriers play an important role in submicrometer MOSFET's operation. Minority carriers photogenerated in the substrate of MOS IC's cause performance degradation [2], [3], such as reduction of the holding time in dynamic RAM's [18]. In bipolar transistors, minority carriers photogenerated in the collector-base depletion layer and in the neutral regions contribute to substrate currents and junction leakage currents [10]. Very recently we have demonstrated that hot-carrier-induced photons are involved in the operation of reach-through avalanche photodiodes for single photon detection [19]. This light emission is expected to set the ultimate performance of solid-state detectors for laser ranging measurements with millimeter spatial resolution.

In order to understand the physical origin of the phenomenon, precise measurements of the spectrally resolved emission efficiency must be compared with theoretical predictions. The aim of our work was to perform such measurements avoiding uncertainties in geometrical and physical parameters. Hence, we employed the simplest conceivable device: a shallow p-n junction. The device is described in Section II. We first verified the quality of our junctions and measured the shape of the emission spectrum. We verified that both the emission intensity and the spectrum shape do not change by decreasing the sam-
pie temperature down to 20 K (Section III). The absolute emission efficiency was then obtained from measurements of optical coupling between two junctions: we quote $2.9 \times 10^{-3}$ photons with energy higher than 1.14 eV emitted per carrier crossing the junction (Section IV). This figure is more than three orders of magnitude higher than that reported in [14]. Section V is devoted to point out why the Bremsstrahlung theory proposed in [13] is definitely not adequate to describe the radiative relaxations of hot carriers in semiconductors. We also discuss other radiative processes which could play a role in the hot-carrier-induced light emission. The comparison between a very recent theoretical analysis [26] and the results of our experiments suggests that spontaneous radiative relaxations of electrons between states in two conduction bands are most likely responsible for the luminescence.

II. THE DEVICE

Pioneering measurements of hot-carrier-induced photon emission were performed on large-area p-n junctions, with breakdown occurring in small spots, called microplasmas. Nowadays, microplasma-free junctions with breakdown uniform all over the junction area can be reliably fabricated.

The schematic cross section of our devices is shown in Fig. 1. The photodiodes are fabricated over an n-substrate with two different p-epilayers [20]: the p$^+$-buried epilayer, 2 $\mu$m thick, provides a low-resistivity path (0.3 $\Omega \cdot$ cm) to the contact side. A very shallow n$^+$-p junction (0.3 $\mu$m from the surface) is obtained by phosphorus predeposition in the upper, low-doped 2.5-$\mu$m p-epilayer (10 $\Omega \cdot$ cm). High-energy photons (>2.0 eV) can thus be measured without severe self-absorption from the top neutral layer. The central window of the n$^+$-p junction is only covered by a 1000-Å SiO$_2$ layer. The avalanching area is defined by a boron implantation, which lowers the breakdown voltage $V_b$ down to 14.3 V at room temperature. The low dopant density in the outer part of the junction and the aluminum field plate prevent edge breakdown. This metal plate also acts as an optical diaphragm for the junction area.

All the measurements were performed with the device reverse-biased a few volts above $V_b$. We detected light emitted from the top of the shallow junction.

III. SPECTRUM MEASUREMENTS

The emission spectrum was detected by a conventional photon counting setup. The sample was mounted inside a cryostat. The light from the sample was collected by a quartz guide, analyzed by an interference filter monochromator, and detected in the range 1.14–3.0 eV by suitable Photomultiplier Tubes (PMT's). The spectra reported in the following are shown corrected for the PMT's quantum efficiency (measured by the manufacturer) and for the wavelength dependence of the optical system transmittance (accurately measured with a recording Spectrophotometer).

![Fig. 1. Schematic cross section of the devices. The avalanching area is defined by a boron implantation, which lowers the breakdown voltage $V_b$ down to 14.3 V at room temperature. The central optical window is covered by a 1000-Å SiO$_2$ layer, not shown in the figure.]

![Fig. 2. Photon emission spectra measured with the sample at room temperature and biased at a reverse current of 1, 2, 4, and 8 mA, respectively. The dashed line shows the experimental data at 8 mA corrected for the estimated self-absorption inside the 0.3-μm silicon surface layer and for the Fresnel transmittance at the silicon-oxide-air interfaces. The corrected spectrum is well fitted above 1.7 eV by a Maxwellian curve with an effective temperature of 4000 K.](image)

Fig. 2 shows typical broad-band spectra detected at room temperature, at different reverse currents. The dashed line represents the experimental data at 8 mA corrected for the estimated self-absorption in the 0.3-μm silicon surface layer and for the Fresnel transmittance at the silicon-oxide-air interfaces. Two features are clearly resolved: i) a broad-band background luminescence with a logarithmic slope corresponding to an average effective temperature of 4000–5000 K; ii) a shoulder of increasing emission intensity at the lower energy end. Spectra of subbandgap photons reported in a previous paper [12] show that this shoulder comes from emission peaks occurring at photon energies below the band edge, that are ascribed to hole transition between two valence bands.

The spectrum shape does not depend on the reverse current. In fact, when a junction is reverse biased above $V_b$, the space charge due to the avalanche current lowers the junction electric field to the breakdown value. By increasing the excess bias, the avalanche current increases but the steady-state junction electric field is always at the breakdown value. It follows that the carrier effective temperature $T_e$ is expected to stay almost the same.

The emission intensity is directly proportional to the current all over the spectrum. This is a signature that a single-particle process is responsible for photon emission, both in the high-energy tail and in the near-bandgap region. In fact, recombination between holes and electrons in the junction depletion layer would lead to a dependence proportional to the square power of the avalanche current. The only recombination process with an intensity propor-
tional to the current could be the recombination between an avalanching carrier reaching the neutral region and a minority carrier. However, since the junction is reverse-biased, there is no charge storage in the neutral regions and this process cannot significantly contribute to photon emission.

We also measured the spectrum cooling the sample down to 20 K. The intensity and the shape of the high-energy region of the spectrum do not change within the experimental errors. We just noticed a slight change in the shape of the low energy shoulder. However measurements of the sub-bandgap spectrum ( photon energies lower than 1.1 eV) are required to better identify the emission feature this shoulder belongs to.

IV. OPTICAL COUPLING MEASUREMENTS

In order to estimate the absolute emission intensity, we chose an arrangement where all the geometrical parameters can be accurately estimated. Fig. 3 shows the experimental setup. Two identical devices were mounted on micrometers, directly opposite each other, and employed as photon emitter and detector. The emitter device was biased at a constant reverse current, thus emitting hot-carrier-induced photons. The other device worked as photon detector biased 1.7 V above $V_p$ in Geiger-mode operation [15], [16], [19], [20]. In avalanche photodiodes biased above $V_p$, a single carrier generated by photon absorption can trigger a diverging avalanche process. In our experimental setup the detector avalanche pulse, in the milliampere range, was sensed by an Active Quenching circuit [21]. The circuit provided an output pulse, synchronous with the avalanche onset, and quenched the current in the detector by lowering the bias voltage below $V_p$. After a well-defined dead time ($T_d = 2.7 \mu s$ in all our measurements) the detector bias was swiftly restored, in order to make possible the detection of another photon. The avalanche rate was recorded by a counter.

All the measurements were performed with the chip holders touching each other. In this condition, the distance $r$ between the emitting junction and the detector was estimated to be less than 1 mm. In order to have higher accuracy, we measured the detected photon count rate first with the devices as close as possible and then increasing their distance by turning the micrometer knobs. The inset of Fig. 3 shows the decrease of the count rate. A perfect $1/r^2$ dependence is found if a value of 0.96 mm is taken for the minimum distance. This value was therefore employed in the following calculations.

The experimental count rate is the sum of the photon rate and the detector dark count rate. By turning off the emitter current, the latter contribution was measured before and after each emission measurement. Since the detector is inactive for the whole dead time $T_d$ after each avalanche pulse, the actual pulse rate $m_0$ is obtained from the measured pulse rate $m$ according to

$$m_0 = \frac{m}{1 - m \cdot T_d}.$$  \hfill (1)

Fig. 3. Experimental setup for the optical coupling measurements: the emitter is biased at a constant reverse current; the detector is operated as photon counter biased 1.7 V above $V_p$. The inset shows the dependence of the detected intensity on the distance $r$ between the two devices.

Fig. 4 shows the photon rate $m_0$ after subtraction of the dark-count rate of the detector. The data are very well proportional to the emitter reverse current $I_{rev}$.

The photon rate $m_0$ is also given by

$$m_0 = \frac{I_{rev}}{q} \cdot \eta_p \cdot \eta_c \cdot \eta_{em} \cdot \eta_d$$  \hfill (2)

where $q$ is the electron charge; $I_{rev}/q$ is the number of carriers flowing per second through the emitter junction; $\eta_p$ is the probability for a carrier crossing the emitter junction to emit a photon with energy higher than 1.14 eV; $\eta_c$ is the fraction of photons emitted within the solid angle subtended by the detector; $\eta_{em}$ is the fraction of these photons escaping the absorption in the top silicon layer and the reflection at the emitter surface; $\eta_d$ is the detection efficiency, defined as the probability for a photon impinging onto the detector sensitive area to be actually detected.

The efficiency $\eta_c$ is estimated by

$$\eta_c = \frac{1}{n^2} \cdot \frac{A_{det}}{4 \pi \cdot r^2}$$  \hfill (3)

where $n$ is the silicon refractive index, $A_{det} = 1 \times 10^{-5}$ cm$^2$ is the detector area, and $r = 0.96$ mm is the distance between the emitter and the detector.

At a given photon energy, the emission efficiency $\eta_{em}$ is

$$\eta_{em} = T \cdot e^{-\alpha \cdot d}$$  \hfill (4)

where $T$ is the Fresnel transmission efficiency for normal incidence, $\alpha$ is the silicon absorption coefficient, and $d = 0.5 \mu m$ is the junction depth.

Fig. 5 shows the detection efficiency $\eta_d$ as a function of the photon energy, computed on the basis of the silicon absorption coefficient [22] and corrected for the avalanche triggering probability of a photogenerated carrier [23]. We verified the agreement between the calculated detection efficiency and the experimental values at 1.49 and 1.96 eV, by using two CW laser sources: an 830-nm laser diode and a HeNe laser (633 nm).

Note that $\eta_c$, $\eta_{em}$, and $\eta_d$ depend on the photon energy via the refractive index $n$ and the absorption coefficient $\alpha$,.
therefore in (2) their product has to be averaged over the corrected spectrum of Fig. 2. We get a value \( \eta_c \cdot \eta_{em} \cdot \eta_d = 2.13 \times 10^{-7} \).

From the above estimate and the experimental results shown in Fig. 4, we obtained \( \eta_{em} = 2.9 \times 10^{-5} \) photons emitted with energy higher than 1.14 eV per carrier crossing the emitter junction. Since photons in the low-energy shoulder (see Fig. 2) account for 20% of the whole detected spectrum, the emission rate of photons in the broadband featureless background is \( 0.8 \times 2.9 \times 10^{-5} = 2.3 \times 10^{-3} \) per carrier crossing the junction.

V. DISCUSSION

The Bremsstrahlung theory proposed by Figielsky and Torun [13] has been thus far accepted because i) the estimate of the absolute emission was in close agreement with the experimental results of [14], and ii) the proposed mechanism could explain the emission independence of the lattice temperature. In the following we will show that these points are not so conclusive as has been believed so far.

Regarding the absolute emission efficiency our measurements demonstrate that the previous experimental estimate [14] was more than three orders of magnitude lower than the actual emission efficiency of hot-carrier-induced photons in avalanching p-n junctions. We ascribe this discrepancy to the quality of the cleaved junctions used in those measurements in the late 1950's. In their samples, avalanche breakdown occurred only in localized "red spots" and the estimate of the current actually flowing through these sites could have been grossly overesti-

\[ Q_c(E) \cdot d\nu = D \cdot \frac{d\nu}{m \cdot E \cdot h\nu} \quad (5) \]

where \( D \) is a numerical coefficient dependent on fundamental constants and on the dielectric constant of the medium, and \( m \) is the free electron mass. What Figielsky and Torun did, was to replace the free electron mass with the electron conductivity effective mass \( m^* \) while taking the vacuum dielectric constant instead of the silicon relative dielectric constant, since for impact parameters of the order of a few Angstroms the carrier interaction is no more screened by the medium polarizability. On the basis of (5) and by assuming a Maxwellian carrier distribution with an effective temperature \( T_e \), they estimated an emission rate between \( 3 \times 10^{-10} \) and \( 5 \times 10^{-8} \) photons in the visible range per carrier crossing the junction [13].

This approach is inadequate to the problem and it is surprising indeed that it has been so widely accepted. Since the observed photons are in the electronvolt range, the radiating electrons should have a kinetic energy well above 1 eV. These carriers are not confined in the conduction band minima and therefore the concept of electron effective mass cannot be properly adopted. Moreover, the actual carrier distribution function is far from being Maxwellian, especially at very high electric fields: a temperature model for the carrier distribution can thus lead to large errors in the estimate, even of orders of magnitude. Therefore, the above Bremsstrahlung theory cannot be considered an acceptable quantitative description of the phenomenon.

The main radiative processes involving hot carriers in semiconductors are: radiative electron–hole recombinations and electron (hole) transitions between two states in conduction (or valence) bands. These conduction-to-conduction band (or valence-to-valence band) transitions can occur i) without any change in the carrier crystal momentum (direct relaxation), ii) assisted by phonons, or iii) assisted by impurities (Bremsstrahlung). The corresponding transition rates must be calculated by taking into account the full complexity of the semiconductor band structure.
Both the direct and the impurity-assisted relaxations do not depend on the lattice temperature. The linear dependence of the measured luminescence on the reverse current (Fig. 4) over the entire detected spectrum rules out any contribution from radiative electron-hole recombinations, even for photon energies close to the bandgap value. Moreover, our results suggest that the photon-assisted processes should not play an important role, since the luminescence intensity does not depend on the lattice temperature (Section III). Very recently, when this work was already completed, Bude et al. [26] published detailed theoretical calculations of carrier radiative relaxations in silicon. They show that the photon emission rate due to the impurity-assisted process (Bremsstrahlung) is negligible compared to direct and phonon-assisted transitions, unless the impurity density is fairly high (\(>5 \times 10^{20} \text{ cm}^{-3}\)). In our devices this dopant density is never reached, hence we can conclude that spontaneous direct carrier relaxations in the conduction and the valence bands are the most likely responsible for the hot-carrier-induced luminescence in p-n junctions.

However, further work is required to fully explain the experimental results from a quantitative standpoint. In fact, a quantitative comparison between the experimental results and the theoretical predictions is the only way to confirm the unavoidable approximations made in the calculations. Some difficulties could arise from the dependence of the carrier distribution function and of the related photon emission rates on the position in the junction depletion layer. In a quantitative theoretical estimate this spatial dependence must be taken into account and properly averaged. However, even a rough estimate of the emission efficiency based on the results reported in [26] would be of interest. Unfortunately, it cannot be performed since the calculated transition rates were not quoted in absolute units.

VI. CONCLUSIONS

We have carefully measured the spectrally resolved emission efficiency of photons from hot-carrier relaxations in avalanching p-n junctions. The spectrum shows two features: i) a broadband background luminescence with an average effective temperature of 4000-5000 K; ii) a shoulder at the lower energy end. We quote \(2.9 \times 10^{-3}\) photons emitted with energy higher than 1.14 eV per carrier crossing the junction. The spectrum shape and the emission intensity above 1.3 eV do not change as the sample temperature ranges from 20 to 300 K, while there is a slight change in the shape of the low-energy shoulder. On the basis of these results and of very recent calculations of the radiative transitions rates of hot carriers we conclude that electron (hole) energy relaxations between states of the conduction (valence) bands are the most likely processes responsible for the hot-carrier-induced luminescence in silicon.

However, both theoretical and experimental work is still required to shed light on the quantitative aspects of the phenomenon. From the theoretical side, it would be worth to quantitatively compare the absolute photon emission efficiency, measured in this work, with careful simulations of the carrier transport and photon emission processes in such simple devices. From the experimental side, spectrally resolved measurements on devices similar to those proposed by Wong [8] could help to check if impurities are involved in the radiative process at least at very high dopant densities.

ACKNOWLEDGMENT

The authors wish to acknowledge S. Cova, E. Gatti, and G. Ripamonti for helpful discussions and suggestions; as well as P. Lovati, C. Samori, and S. Masei for their technical support. The devices were fabricated by SGS-Thomson Microelectronics, Castelletto di Settimo, Milano, Italy.

REFERENCES


Franco Zappa was born in Milano, Italy, in November 1965. He received the Electronic Engineering degree at the Politecnico di Milano in 1989.

After graduating, he joined the Department of Electronics at the Politecnico di Milano, where he is currently pursuing the Ph.D. degree. His research interests are in the fields of semiconductor photodetectors and optical fiber characterization.

Stefano Bigiardi received the degree in physics (cum laude) from the University of Parma, Italy, in 1990.

His current interest is radiation induced by hot electrons in semiconductor devices. At present he is working at the Department of Physics of the University of Parma.

Andrea L. Lacaita (M’90) was born in Manduria, Italy, in 1962. He received the Laurea degree in nuclear engineering in 1985 at the Politecnico of Milano, Milan, Italy.

In 1987 he joined the Italian National Research Council as Researcher. In 1990 he was a Visiting Scientist at the AT&T Bell Laboratories, Murray Hill, NJ, where he worked on photorefractive effects in superlattices. In 1992 he was appointed Associate Professor of Electronics at the Politecnico of Milano. His current research interests are the development of avalanche photodiodes for single photon detection, hot-carrier transport in semiconductor devices, and new experimental methods for characterization of semiconductor materials and devices.

Manfredo Manfredi received the degree in physics from the University of Milano, Italy, in 1965.

Since 1968 he has been working at the University of Parma where he is teaching and pursuing researches on optical properties of ionic crystals and semiconductor devices.