A Probe Detector for Defectivity Assessment in p-n Junctions

Alfio Zanchi, Student Member, IEEE, Franco Zappa, and Massimo Ghioni, Member, IEEE

Abstract—In this paper, we present a process probe capable of measuring the avalanche ignition rate of the generation centers, in order to investigate some process-dependent morphological properties of p-n junctions. In particular, we report a nonlinear dependence of the defectivity with the area of circular junctions, which can be ascribed to a radially growing density of generation centers, like dopant clusters. This hypothesis has been verified by means of both microscopic inspection of the probes and comparison with alternative probe geometries. Technological hints are finally provided to counteract the defectivity, thus leading to potential improvements in the fabrication of microelectronic devices.

Index Terms—Gettering, integrated circuit manufacture, manufacturing testing, p-n junctions, semiconductor device fabrication.

I. INTRODUCTION

THE quality of technological semiconductor processing is one of the driving requisites of modern microelectronics that cannot be relaxed in any way. The current leakage of devices and the quality of shallow junctions are of major concern among the many technological nonidealities, since they lead to power consumption and overall performance degradation of electronics systems. Though the most care has been traditionally devoted to the leakage due to perimetrical impurities, bulk defects also play a role [1], [2]. Therefore, besides the efforts to purify the starting silicon quality, a search for defect-free technological steps has long been carried on.

The cleanliness of the fabrication process can be assessed by evaluating the performance of devices whose characteristics are especially sensitive to the quality of technology. Such probes, that can prove their usefulness in testing the process steps' efficiency, are ultra-high sensitivity photodiodes. In particular, single-photon avalanche diodes (SPAD’s) are sensing devices capable of detecting the generation of one single carrier within their active region, by means of a macroscopic current pulse in the milliamp range: such generation can be due either to the arrival of one light photon, or to any other thermal generation event [3]. The working principle of such probes is described in Section I. As photodetectors, their potentially excellent performance is degraded by the presence of unwanted avalanche ignitions triggered by phenomena other than photon absorption: the so-called “dark” counting rate. On the other hand, as probe devices they can be usefully exploited to measure the generation rate in the semiconductor, hence the quality of the junction under test. Moreover, since the higher the electric field, the higher the carrier generation, such devices are excellent candidates for the localization of the lattice defects, such as dopant clusters, dislocations, stacking faults, etc. Throughout the paper, it will be shown how the use of avalanching junctions as process monitors for a technological quality check allows intuitive, useful insights into the defect formation and propagation mechanisms. Some technological adjustments useful to rule out these phenomena are derived from the experimental inspection of the probes.

Up to now, hot spots (where electric field has localized peaks) had always been considered uniformly distributed over the junction area. Thanks to the measurements performed on the probes and reported in Section II, we show that this does not hold in general. In Section III, we derive how the defect distribution varies with the diameter of the junction, progressively increasing moving toward the edges. This conclusion is consistent also with other experimental data reported in literature, as in [4]; and it explains, for example, why larger area photodiodes undergo an exceedingly detrimental dark counting increase. In Section IV the nonuniform defect distribution is obtained by means of different experimental techniques, thus confirming the correctness of the proposed probing method. Eventually, in Section V, a physically based explanation of the growth of defect density is sought and found in the gettering-induced centrifugal movement of dopant clusters.

The improvement of drive-in uniformity, annealing and diffusion techniques, as well as gettering, will allow a better control of the defects during the tailoring of a given technology. The refinements of these aspects will lead to the fabrication of junctions with a better ideality factor, Zeners with a lower excess noise, avalanche photodiodes (APD’s) with reduced unmultiplied dark current, and a reduced leakage in all devices in which one or more junctions are operated in reverse-biased regime.

II. OPERATING PRINCIPLES OF THE PROBE DEVICE

Unlike conventional APD’s, where the amount of reverse current is proportional to the photon flow (analog behavior), SPAD’s return an on-off current pulse synchronous to the avalanche ignition (due to either a single photon absorption or other carrier generation means), in a Geiger-like operation (digital response) [3]. The physical mechanism that allows SPAD’s to detect one single photon is the onset of a diverging internal current buildup, provided by the avalanche multiplication of carriers that establishes when the device is biased beyond its breakdown voltage. Conventional APD’s are instead operated below their breakdown threshold.
Fig. 1 shows the classical structure of a circular SPAD. Due to its simple layout, one can include this device in most micro-electronic technologies employed nowadays. The cathode of the diode is a large n⁺ diffusion (5 ± 100 µm diameter) into a p epi-layer, surrounded by a collecting sinker, that conveys the current to the anode metallization. The actual avalanching area and the size of the depleted region can be technologically tailored by means of an additional p⁺ enrichment diffusion, that defines the high-field active area.

Let us briefly clarify the working principle of such a photodetector. The incident photon penetrates into the depleted region of the reverse-biased junction according to its wavelength, and statistically it is absorbed at a given depth. Thanks to the released energy, a silicon link can be broken, thus creating an electron and a hole which become able to generate other e-h pairs, and so on, due to the strong electric field in the space charge region. Since the device is biased above breakdown, the just triggered avalanche ignition process builds up. Eventually, the entire active region of the device will be conducting current, whose final amount is a function of the reverse bias in excess to the junction's breakdown voltage and its space charge series resistance.

After the avalanche current has settled, the quiescent bias condition must be restored; therefore the process needs to be extinguished by switching the detector off. The quenching of the SPAD is accomplished via a dedicated active quenching circuitry (AQC) [3], which basically comprises a voltage comparator that senses the onset of the current flow through a ballast resistor, and activates a feedback network that forcibly lowers the voltage across the SPAD. The device is kept quenched for a certain time duration (a few tens of nanoseconds) in order to prevent spurious reignition due to the release of carriers captured by traps in the semiconductor, during the preceding avalanche phase (afterpulsing phenomenon). Fig. 2 illustrates the typical digital output of the circuit, when the detector is triggered at a rate of about 10 kcps and stays quenched for 36 ns after each ignition.

The process that harms the sensitivity of SPAD’s as photon counters is the unavoidable generation of electron-hole pairs, due to thermal lattice agitation and other related mechanisms different than photon absorption. Indeed, those spurious ignitions lead to current pulses undistinguishable from those produced by photons, thus impairing the precise evaluation of the real photon flux. Such “dark” counting is equivalent to the noise that sets the minimum detectable signal for analog detectors.

If one is not interested in counting photons, SPAD’s can be kept in the dark and used as probes on a given wafer, for measuring the overall carrier generation rate and ranking the quality of the technological process employed. In fact, this is the operating condition that we adopted in the following, and whose typical result is shown in Fig. 2.

III. MEASUREMENT OF THE GENERATION RATE

We processed various wafers, with minor modifications in the steps following the diffusion of the junction under test. The dose of the enrichment boron ion-implantation was $1 \times 10^{15}$ cm$^{-2}$ at 100 keV, with an annealing of 6 h at 1000 °C in nitrogen; the dose of the ion-implanted phosphorus shallow junction was $2 \times 10^{14}$ cm$^{-2}$ at 80 keV. The processing steps that diversify the wafers are shown in Table I. Wafer 2 was annealed for 3 h at 950 °C in nitrogen, before opening the contacts; wafer 3 and wafer 4 were annealed for 1 h at 1000 °C in nitrogen, but in the latter a highly doped phosphorus isolation diffusion was implanted 20 µm outside the sinker, for gettering purposes. Every chip chosen out of the specimens contained one in-line array
TABLE I
PROCESSING STEPS THAT DIVERSIFY THE WAFERS

<table>
<thead>
<tr>
<th></th>
<th>Wafer 2</th>
<th>Wafer 3</th>
<th>Wafer 4</th>
</tr>
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<tbody>
<tr>
<td>isolation implant</td>
<td>-</td>
<td>-</td>
<td>Phosphorus 4x10^14 cm^-2 150keV</td>
</tr>
<tr>
<td>final annealing</td>
<td>3 h 950°C N₂</td>
<td>1 h 1,000°C N₂</td>
<td>1 h 1,000°C N₂</td>
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Fig. 3. Characteristic flickering near the breakdown knee of V-I curve, a clear sign of the low thermal generation rate.

of circular SPADs; each array is composed by ten identical devices, with a common epilayer anode. Several groups of array detectors were laid out, with different enrichment and shallow junctions diameters, thus allowing the evaluation of the junction’s behavior. Since only the region with the enrichment diffusion will be driven into avalanche (the so-called active area), in the following we will specify only that diameter.

First of all, the various devices were tested by means of a Tektronix 370 analog curve tracer. From the current-voltage curves, the essentials of each junction (breakdown voltage, reverse series resistance, leakage current) were measured for each set of samples. For instance, in wafer 2 the 50 μm-diameter device probes had a mean breakdown voltage of 74.1 V with a dispersion of 7.6%, and a mean reverse resistance of 5.5 kΩ. It is worth noting that those data can be measured when the junction presents a sufficiently high rate of avalanche ignitions. Otherwise, if the processing was very clean, the generation rate is so low that no current could be observed for tens of milliseconds even after the voltage sweeps above the breakdown value, as shown in Fig. 3. Such flickering is more marked, for lower generation rates. Allowing a weak light infiltration into the obscured probe station is an effective way to obtain well-defined reverse characteristic plots, with a completely vanished flickering.

After that, the devices were completely obscured by closing the probe station, thus assuring that any avalanche triggering was due to a thermal generation. The anode of each junction was reverse-biased above its breakdown by an excess voltage of 5 V, while the cathode was driven by an active quenching circuit. Every ignition of the junction under test is detected by the AQC and collected by an HP5335A universal counter, with an 18 s-integration time. The spreading of the number of counts around the average value is reduced in this way to less than 4%.

Some experimental results are summarized in Table II. Note that the thermal generation rate proves acceptable for the smaller junctions, while it worsens appreciably as the diameter exceeds 50 μm; this is not simply due to the volume increase of the depleted region, as will be shown in the following. Since large active areas are highly desirable not only for photodetectors, but also for many other microelectronics devices (e.g., power transistors), we investigated the origin of this phenomenon, in order to counteract it with proper technological adjustments.

IV. EVALUATION OF THE DEFECT DENSITY DISTRIBUTION

Fig. 4 shows in a log-log plot the three sets of data collected in Table II. The expected trend of the generation rate would be proportional to the volume of the depleted region, i.e., the square of the active area diameter, since the depletion layer thickness is constant for similar devices at a given reverse bias. Instead, as can be seen from Fig. 4, the increase of avalanche ignitions is steeper than expected, and it follows a fairly rigorous straight power-law increase. The same trend is followed by other experimental data, as the ones published in [4] and plotted for ease of comparison in Fig. 5.

Though the processing performed on our wafers and those fabricated in [4] is definitely different, the straight-line fitting...
is pursued anyway. This is a clear signature that a well-defined mechanism is responsible for the increase of generation centers within the junctions.

As stated already, if the carrier generation were ascribed to lattice defects, with a reasonable uniform distribution, the ignition rate should scale according to

\[ \text{Generation rate} = N \cdot \pi \cdot R^2 \]  

(1)

in which \( N \) is a coefficient proportional to the defect density of the junction and \( R \) is the outer radius of the avalanching active area. Instead, from the interpolation of the measured points, we recognize that the best fit is achieved when the defects follow a nonuniform distribution. More precisely, the generation centers’ density should vary with the radius of the active area (the invariance with respect to the azimuth coordinate, \( \varphi \), is guaranteed by the cylindrical symmetry chosen for the test device). In fact, we can write:

\[ \text{Generation rate} = \int_{\text{active area}} p(r, \varphi) \cdot r \, d\varphi \, dr \]  

(2)

where \( p(r, \varphi) \) is the defect density per unity area. The dependence experimentally found can be encompassed by a radial distribution as

\[ p(r, \varphi) = k \cdot r^n \]  

(3)

where \( r \) is the distance from the junction's center, \( k \) is a proportionality coefficient, and \( n \) is the exponential growth factor. Fig. 6 shows such a defect density for \( n < 1 \).

By integrating all the generation centers from the core of the junction up to its edge, we get the total rate

\[ \text{Generation rate} = \int_{\text{active area}} p(r, \varphi) \cdot r \, d\varphi \, dr \]

\[ = \int_0^R \int_0^{2\pi} k r^n \cdot r \, d\varphi \, dr = 2\pi \cdot k \cdot \int_0^R r^{n+1} \, dr \]

\[ = 2\pi \cdot k \cdot \frac{R^{n+1}}{n+1} \]  

(4)

From Table II and Fig. 4 the parameters \( k \) and \( n \) in (3) can be estimated. If the radius \( R \) is expressed in microns, the parameters are found to be as follows.

- Wafer 2: \( n = 0.77 \), \( k = 0.035 \)
- Wafer 3: \( n = 0.74 \), \( k = 0.73 \)
- Wafer 4: \( n = 0.68 \), \( k = 0.35 \)
- Ref. [4]: \( n = 3.03 \), \( k = 0.0002 \)

In all of our three wafers, the radial defect density increases slightly less than linearly; for instance, for the wafer 2 we get

\[ p(r, \varphi) = 0.035 \cdot r^{0.77} \]  

(5)

and a similar exponent \((n \approx 0.7)\) is found for the other two wafers. The higher temperature annealing of wafers 3 and 4, compared to wafer 2, yield a sensible reduction of generation centers [5] within the active areas \((k\) decreases in fact). Moreover, the additional phosphorus isolation diffusion surrounding the junctions in wafer 4 proves to be very effective in further reducing the defect density, compared to wafer 3. Instead in [4] the dopant drive-in was made via a laser-annealing technique, that
accomplishes a remarkably better defect reduction (very small $k$); however, the gettering efficiency of the structure surrounding the active area appears to be rather poor, since the increase in the defect density is very steep (high $n$). The technique of laser-annealing used in order to free up the junction from defects shows therefore a rather limited spatial range of efficiency.

The split among wafers 2, 3, and 4 does not affect the long-range gettering action on the radial distribution of defects (since $n$ does not change), but enhances the overall quality of the junction (hence, lower $k$). This action can be explained by taking into account the effectiveness of gettering media on the movement of defect clusters away from the active junction. The gettering toward the edges of the junction improves when an annealing at high and uniform temperature is used, since it eases the motion of defects toward the periphery of the active area, where they will no longer spoil device performance.

Because the gettering phenomenon takes place outside the junction where it attracts the defects, the spatial distribution of generation centers grows when closer to the junction edges. For instance, the isolation diffusion designed all around the active areas in wafer 4 works as a stronger gettering attractor, thus yielding lower $k$ (better defect collection efficiency), while the almost unchanged $n$ implies that the origin of the defects is nearly the same.

V. SPATIAL MAPPING OF DEFECTS

The hypothesis of a radially growing distribution of defects finds support from another experimental evidence, able to spatially localize the hot-spots in avalanching junctions [6], [7]. Fig. 7 shows three images obtained by an Infrared Emission Microscope (IEM), when different reverse currents flow through an avalanching junction.

The pictures can be regarded as snapshots of three successive phases of the turn-on transient in a photodiode having circular active area. The SPAD was kept in the dark, while the junction was forced above breakdown at different excess biases, leading to different dc reverse currents. The annular metallization is the cathode of the 200 $\mu$m-diameter SPAD, whereas the square metal path is the anode. The visible hot-spots are due to current filaments flowing through microplasmas, i.e., localized areas where a peaked electric field causes the onset of a local multiplication process and the generation of hot (highly energetic) carriers. Such hot-spots often stand out clearly visible by eye even with a standard optical microscope, if the metallization does not cover the avalanching region as in the probe devices used.

The hot-spot pattern maintains a concentric shape. Moreover, the avalanche mechanism begins from the extreme periphery of the active area (at weak reverse bias, shown on the left of Fig. 7); then it spreads toward the center of the detector; eventually, at 3 mA, the whole active area is ignited, while keeping the maximum brightness always near the edge. Simulations prove that the electric field is uniform within the enrichment diffusion, thus ruling out any electrostatic-related nonhomogeneity of the luminescence. Therefore, the density of hot-spots can be related to the distribution of generation centers. From a qualitative inspection of the sequence in Fig. 4 we conclude that the density of generation centers grows with the increasing distance from the junction’s core.

Moreover, we treated the wafers with a Secco-etch [8], able to highlight the location of some kinds of lattice imperfections. Fig. 8 shows the photographs of two different probe junctions, with round and cigar-like shapes, found on wafer 2 and 4. As expected, the majority of defects lie at the junction edge, and wafer 4 shows a dramatically reduced defect density.

In order to check the distribution of lattice defects also in more complex microelectronic technologies, we applied the previous recipes on a new batch of wafers produced on silicon on insulator (SOI) substrates, with 1 $\mu$m-thick oxide trenches dug between adjacent junctions. Fig. 9 shows the photograph of a circular probe junction surrounded by a square trench at the early steps of the fabrication process, after trench anisotropic etch and refill and phosphorus isolation diffusion. As can be seen, prior to the final enrichment and shallow diffusion processing (shown with dashed circles) the defects and dislocations are almost uniformly spread, as revealed by the Secco-etch. As expected, the great majority of defects lie very close to the trenches; denser encroachments are visible at the four corners of the layout, and near the trench opening that appears on the right side of the square.

The tunneling electron microscope (TEM) image shown in Fig. 10 confirms that the trench opening introduces stress and defects in the lattice. However, the region where the active area of the junction will be formed in subsequent processing is sufficiently far from the crowding of these imperfections (though the overall defect density may have increased [9]).

Away from the trench, the pitfall distribution appears to be nearly random and does not show the increase outlined in Figs. 4, 7, and 8. We can conclude that it is the following processing steps (diffusions and oxidations) that, besides introducing new defects, are mainly responsible for gettering and moving them away from the active area.
VI. PHYSICAL INTERPRETATION

There is no reason to consider the distribution of the dopant after the implantation to be nonuniform. Also, after the subsequent annealing step, the strong initial amount of phosphorus can move toward the border of the active area [10], [11]. The Wiener diffusion process would mix the clusters of dopant in a wider and wider area, while keeping them always homogeneously scattered into the silicon. Nonetheless, due to the gettering action of the oxide surrounding the anode [12], the implanted phosphorus doping would undergo a net displacement and travel toward the edges of the structure. Therefore, the final distribution of the defects would be in principle isotropic in azimuth, while rising progressively with the distance from the junction center, as in the surface drawn in Fig. 6. In other planar structures, some other heavily doped diffusions or polysilicon areas [13] can work as effective gettering sites.

As a final crosscheck of what is stated above, we characterized a probe junction with an alternative geometry than the round one. These detectors were designed to have a cigarlike shape, as shown in Fig. 11. These new junctions have a breakdown voltage of 100 V, with a spreading of 6%, and resistances in reverse-bias of about 3.7 kΩ. It goes without saying that the gettering dynamics is much more effective in this new topology, thanks to the increase of the perimetal extension of this stretched shape, whereas the round geometry is the one that minimizes the linear extension of the border for a given surface. Due to the enhanced gettering clean-up effect provided by the extended edge, the active area of these cigarlike probes is poorer in generation centers; thus,
the ignition rate is reduced. Moreover, the rate scales now almost proportionally to the area of the device (i.e., $n = 0$ in (3)). Table III summarizes the experimental data collected for some kinds of cigarlike junctions implemented on different test wafers. Again, all data were averaged on several measurements taken on dice randomly chosen from the hundreds available on the wafers.

For wafer 6, when comparing the cigar area $200 \times 5 \, \mu m^2$ versus $500 \times 5 \, \mu m^2$ (i.e., a factor 1:2.5) we obtain a proportional scaling in the generation rate: the count increases accordingly from 15 000 to 39 500 (1:2.6). This result indicates that an effective defect gettering has normalized the cluster poisoning that impaired the performance of round SPAD’s, restoring the usual area-proportional thermal count behavior. For both the wafers in Table III a high dark counting rate has also been observed for the wider cigars ($100 \times 10 \, \mu m^2$) with respect to the narrow ones. Again, this could be ascribed to the reduced gettering efficiency of the lateral side of the former cigars, that implies a more than double degradation when compared with the latter ones.

### VII. Conclusion

We have tested the usefulness of a simple avalanching junction, derived from our knowledge in single-photon avalanche photodiodes, for measuring the defectivity of silicon wafers. By measuring the avalanche ignition rate, it has been possible to evaluate the density of generation centers versus the radial position in shallow junctions. The experimental results show that the distribution is not uniform. This is a clear evidence that carrier generation is mainly due to lattice defects, whose density radially grows moving from the junction’s center to its edges.

The physical mechanism responsible for such nonuniform distribution has been ascribed to the radial movement of dopant clusters toward the gettering media outside the active junctions. The main gettering attractors proved to be the highly doped phosphorus isolation diffusion and the thermal oxide encroachment at the edge of the photolithographic opening of the shallow diffusion. The overall quality of the wafer enhances with a higher temperature annealing step having a shorter duration.

Because the quality of junctions is an important issue in many microelectronic devices (not only reverse-biased diodes, Zeners, APD’s and power transistors) the investigation of such defectivity is a must. Since the proposed junction probes have a conveniently simple structure, they can be included on most test wafers during the tweaking of new production processes. The measure of their avalanche ignition rate, as in single-photon counting apparatus, may be used as a benchmark for assessing the cleanliness of the manufacturing line and the efficacy of the programmed sequence of gettering steps.

### Acknowledgment

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### References


### Table III

**Average Avalanche Ignition Rate for Cigarlike Junctions**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Wafer 5</th>
<th>Wafer 6</th>
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<tbody>
<tr>
<td>100×10 ( \mu m^2 )</td>
<td>93,000</td>
<td>49,000</td>
</tr>
<tr>
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<td>36,000</td>
<td>15,000</td>
</tr>
<tr>
<td>500×5 ( \mu m^2 )</td>
<td>-</td>
<td>39,500</td>
</tr>
</tbody>
</table>

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**Alfio Zanchi** (S’94) was born in Alzano Lombardo, Bergamo, Italy, in 1971. He graduated in electronics engineering from the Politecnico di Milano, Italy in 1996, where he worked on the design of a digital filter for decimation of a high-frequency sigma-delta converter. He is currently a Ph.D. candidate at Politecnico di Milano, where he is involved in the development of analog integrated circuits for wireless communication front-end. From 1996 to 1999, he was a Consultant with STMicroelectronics, Catania, Italy. He collaborated to develop new experimental methods for the characterization of semiconductor device processing technology.
Franco Zappa (M’2000) was born in Milano, Italy, in 1965. In 1989, graduated in electronics engineering, and received the Ph.D. degree in electronics and communications, both from Politecnico di Milano, Italy, in 1989 and 1993, respectively.

In 1994, he was a Visiting Scientist at the NMRC National Microelectronics Research Centre, Cork, Ireland, where he designed new integrated circuits for driving single-photon avalanche diodes. Since 1998, he has been an Associate Professor of electronics with the Department of Electronics and Information, Politecnico di Milano. His interests are in the design and applications of avalanche photodiodes in the visible and near-infrared wavelength ranges, and the design of photodetector arrays for imaging and the related electronics.

Massimo Ghioni (M’91) was born in Monza, Italy, in 1962. He received the Laurea degree in nuclear engineering from the Politecnico di Milano, Italy, in 1987.

He is Associate Professor of Electronics with the Department of Electronics and Information, Politecnico di Milano. In 1992 he was a Visiting Scientist at the IBM T. J. Watson Research Center, Yorktown Heights, NY, where he worked on silicon photodetectors for integrated optical receivers. His current research interest include the design of avalanche photodiodes for single photon detection and the development of fast electronic circuits for picosecond timing applications.