Abstract—Single photon counting plays an essential role for a wide variety of applications, ranging from biomedical research to astronomy. In gamma-ray astronomy, the Cherenkov telescope MAGIC is used to detect Cherenkov photons generated in atmospheric air showers. Since the flux of Cherenkov photons from air showers is low, the development of new single photon detectors with high quantum efficiency is necessary. The concept of the Back Illuminated Drift Silicon Photomultiplier (BID SiPM) is a novel detector design for single photon counting. It combines the principles of a silicon photomultiplier (SiPM) and a drift diode. The back illuminated drift silicon photomultiplier is operated as back illuminated detector thus providing a fill factor of 100%. A high quantum efficiency of about 80% in a wavelength region of 300 – 1000 nm can be achieved. The drift region is used to focus electrons from the back through the depleted bulk to the small point-like avalanche region. The time jitter of the electrons limits the time resolution of the detector to about 1 ns as simulation results show. A prototype of an avalanche region which can be combined with a drift structure was produced at the MPI Semiconductor Laboratory as proof of principle. The detector concept and results of measurements of dark rate and leakage current are presented.

Index Terms—BID SiPM, Silicon Photomultiplier, Avalanche Diode, Single Photon Counting, High Quantum Efficiency, Back Illumination

I. INTRODUCTION

Detection of low light fluxes and single photon counting is an issue in many experiments ranging from medical research [1] to astronomy [2]. The improvement of detectors for single photon counting is therefore of utmost importance. In ground based gamma-ray astronomy, low fluxes of Cherenkov photons are detected by imaging of extended air showers which develop in the atmosphere. Extended air showers are generated mainly by incident hadrons of cosmic origin [3] and also, a small fraction of air showers is generated by incident gammarays and electrons. As a rule of thumb, there is a linear relationship between energy of the primary incident particle and the amount of Cherenkov photons generated [4]:

The smaller the energy of the incident particle, the smaller the amount of Cherenkov photons produced during shower development. The MAGIC (Major Advanced Gamma - ray Imaging Cherenkov) telescope is currently the world’s largest Cherenkov telescope with a mirror diameter of 17 m [5]. In order to lower the energy threshold of the MAGIC telescope and give good overlap of data received with satellites in the range of ca. 10 GeV [6], the development of detectors with high quantum efficiency is necessary to resolve images of showers generated by gamma-rays in the energy range mentioned above. Currently the camera of the MAGIC telescope consists of 600 photomultipliers with peak quantum efficiency of ca. 30% at a wavelength of 400 nm [7]. Measurements in the range of 90 GeV – 15 TeV are successfully performed [8]. The spectrum of Cherenkov radiation has the maximum amount of photons emitted in the ultraviolet and blue range. Part of the UV radiation is cut off by absorption of the atmosphere for wavelength of less than \( \approx 300 \text{ nm} \) [9]. The amount of Cherenkov radiation per unit wavelength decreases with increasing wavelength so that for wavelength of more than 650 nm the light of the night sky (LONS, average rate of \( 10^{12} \text{ photons/m}^2/\text{s/sr} \)) background starts to dominate and the short (1 ns) flashes of Cherenkov radiation cannot be distinguished from LONS. Thus, the requirements for a detector to be used in a Cherenkov telescope camera are:

1.) high quantum efficiency at the wavelengths of 300 – 600 nm
2.) short integration time for suppression of the light of night sky background (LONS)
3.) to allow for high trigger rates: detector dead time should be small (small capacitance)
4.) appropriate intrinsic gain (105) to avoid sophisticated preamplifiers
5.) time resolution \( \approx 1 \text{ ns} \) to resolve shower images of Cherenkov photons from air showers
6.) pixel size desired to be about 1 cm²

One approach to reach this goal is the development of the Back Illuminated Drift Silicon Photomultiplier (BID SiPM).
A. Properties of Silicon Photomultipliers

Like conventional silicon photomultipliers [11], [12], the BID SiPM consists of an array of many individual avalanche cells (≈ 1000/mm²) on common silicon substrate. Each individual cell is operated in limited Geiger Mode, i.e. slightly above breakdown voltage, like single photon avalanche diodes (SPADs [13]). Every cell is connected to a quenching resistor (passive quenching) and coupling capacitance. All cells are connected and readout in parallel. The recovery time depends on the capacitance and quenching resistor of a single cell \( \tau = R_{\text{pixel}} \times C_{\text{pixel}} \) [14]. The SiPM signal saturates with increased light intensity, the dynamic range depends on the number of cells per pixel [15].

Two main advantages of SiPMs are low operational voltages (20 – 100 Volt) and insensitivity to magnetic field. Main disadvantage of conventional front illuminated SiPMs is the small fill factor which limits the photon detection efficiency PDE to 40% [16], if we define PDE = \( \epsilon_{\text{geo}} \times \epsilon_{\text{QE}} \) where \( \epsilon_{\text{geo}} \) is the geometrical efficiency and QE is the quantum efficiency. Another disadvantage of SiPM is the cell-to-cell crosstalk resulting from photon emission during avalanche breakdown [15], [17]. In order to produce a detector with high quantum efficiency (≈ 80%) by increasing the fill factor up to 100 %, the concept of the BID SiPM was developed [18], [19], [20].

B. Detector Concept of the Back Illuminated Drift Silicon Photomultiplier

The BID SiPM combines the principle of an SiPMs and a drift diode. A schematic view of the concept of a single cell is shown in Figure 1. The detector will be operated as back illuminated device. The electron which is generated by an incident photon close to the homogeneous entrance window at the back of the device drifts to a small, point-like avalanche region located close to the front side of the device. The entrance window can be engineered using planar technology increasing quantum efficiency up to 80% in a wavelength region of 300 - 1000 nm [21]. The advantage of a small (< 25µm diameter) avalanche region is the small parasitic capacitance (≈15 fF) and therefore the small recovery time. The latter can be estimated to be of the order of ≈ 100 ns if quenching value of resistor R (≈ 1 MΩ) and coupling capacitance C (few fF) are optimized [14]. Moreover the amount of generated charge is small when capacitance is small (\( Q = C \times U_{\text{overbias}} \) when operated at 10-15% overbias). This is important to counteract photon induced cell-to-cell crosstalk, since efficiency for photon emission during avalanche breakdown is proportional to the amount of generated charge (≈ 2.9 \times 10^{-5} photons with an energy higher than 1.14 eV per carrier crossing the p-n junction [17]). To guarantee full charge collection, the drift region has to be optimized and the corresponding voltages have to be applied at the back and at the drift rings which are located on the front side. In contrast to conventional SiPM, for the BID SiPM the back cannot be used to apply the reverse bias for the avalanche region, so that a new concept for a high field was developed. In this novel concept, the reverse bias voltage can be applied on the front side of the device. In order to avoid edge breakdown, the high field region is produced in the inner part of the anode region and the implantation is modulated, such that the edges of the anode are not involved in high field region. The drift region limits the time resolution of the device to about 1 ns [22], which is sufficient for a detector of a new MAGIC camera. To prove the principle of the newly developed concept, test structures of avalanche region were produced at the Semiconductor Laboratory of the Max-Planck-Institute for Physics and the Max-Planck-Institute for Extraterrestrial Physics.

C. Measurements and Results

Among a wide variety of test structures, we produced arrays (SiPM) of 20 × 25 avalanche cells connected in parallel and each having a quenching resistor of ca. 1 MΩ and a coupling capacitance of 30 – 100 fF. The average cell pitch is 130 – 200 µm. The produced SiPMs are currently operated as front illuminated device, since the drift region is not yet implemented. Isolated single cells, used as a building block for the arrays, are also available. High field region diameter varies from 5, 10, 25, 26 µm.

The dark rate of a single avalanche cell (high field diameter 25 µm) at 1.7 ± 0.17 kHz at ca. 10 % overbias. When decreasing the temperature from \( T = +20^\circ \text{Celsius} \) to \( T = -70^\circ \text{Celsius} \), the dark rate decreases by orders of magnitude, though it does not follow exactly the theoretical curve calculated from pure Shockley-Read-Hall generation \( \propto T^2 \exp\left(-\frac{1}{2kT}U_{\text{overbias}}\right) \) as shown in Figure 2. The dark rate measured is a factor of 10 higher than expected when cooled to \( T = -70^\circ \text{Celsius} \). This increased dark rate at lower temperature might be a contribution from afterpulsing, diffusion...
of electrons into the high field region or tunneling. Dark rate of single cell was measured by keeping pulse height constant when decreasing temperature. The change of the breakdown voltage as a function of temperature is shown in Figure 3. Figure 4 shows the measurement of pulse height vs. bias voltage for $T = 0, 10, 20^\circ$ Celsius.

To illustrate the operation of single photon counting, an SiPM consisting of $20 \times 25$ cells was illuminated by diffused laser light (682 nm). Each cell of the illuminated SiPM has a high field region of 10 $\mu$m diameter. The resulting photon spectrum is shown in Figure 5. The first peak corresponds to single photons and has the rms of ca. 5% thus proving a high homogeneity of the pulse area over the whole array.

To test the quality of our production, the uniformity of breakdown voltage and leakage current were measured using $1 \text{ mm}^2$ area avalanche diode with a resistor of 1 M$\Omega$ connected externally. Results show that both, a high uniformity of breakdown voltage and a good uniformity of leakage current over the whole wafer are achieved. An overlay of 6 IV curves taken at different positions of the wafer is shown in Figure 6. It can also be seen, that the IV characteristic is not accompanied by generation of microplasma or early breakdown. In order to separate the edge and the center current avalanche diodes with area 1 mm$^2$ having different circumference of 4 mm, 5 mm, 8.5 mm, 16.25 mm were measured. If extrapolated to a circumference of 0 mm, a value of center current of ca. 0.7 pA was deduced as shown in Figure 7. A comparison of the leakage current derived from avalanche diodes of $1 \text{ mm}^2$ area ($\approx 4.4 \text{ MHz/mm}^2$) with the dark rate of a single SiPM cell ($\approx 3.5 \text{ MHz/mm}^2$) show good agreement at room temperature. Assuming a cell size of $10 \times 10 \mu$m and a pitch of 70 $\mu$m, the avalanche region as fraction of pixel is $\approx 1/50$, so that avalanche region will contribute to dark rate with ca. 70 kHz/mm$^2$. We estimate that the dark rate of the BID SiPM will be dominated by the contribution of the leakage current which is produced in the bulk and collected by drift region to reach the avalanche region. Assuming a leakage current of $\approx 1 \text{ pA/mm}^2$, we then
Fig. 6. Overlay of IV curves taken at 6 different positions of the wafer of 1 mm² area avalanche diodes, 1 MΩ externally connected, \( T = 24° \) Celsius

Fig. 7. Extrapolation of center current for avalanche diodes with different circumference: 4 mm, 5 mm, 8.5 mm, 16.25 mm and same area 1 mm², diodes were measured at \( T = 24° \) Celsius

estimate the dark rate about 10 MHz/mm² for a BID SiPM when operated at room temperature.

II. CONCLUSION

The production of avalanche test structures for the BID SiPM was successful. Test structures show avalanche breakdown as expected and no edge breakdown. Typical breakdown voltage is at 37.0 ± 0.1 Volt and dark rate for a single avalanche cell (high field diameter 25 \( \mu \)m) is measured to be 1.7 ± 0.17 kHz at room temperature. Moreover we achieved a good uniformity of breakdown voltage and leakage current over the whole wafer in this production of test structures. The next step is the design and production with implemented drift structure.

REFERENCES


