High-uniformity 1 × 64 linear arrays of silicon carbide avalanche photodiode

Xingye Zhou, Xin Tan, Yuanjie Lv, Jia Li, Shixiong Liang, Zhihong Feng✉ and Shujun Cai

In this Letter, high-uniformity 1 × 64 linear arrays of 4H-SiC avalanche photodiode (APD) are reported for ultraviolet detection. Multi-cycle inductively coupled plasma dry etching was adopted for the bevelled mesa formation, during which the wafers were rotated with a small angle for each cycle to suppress the process variation. As a result, a high pixel yield of 100% and a high-uniformity breakdown voltage with a fluctuation of smaller than 0.5 V are achieved for the fabricated 1 × 64 4H-SiC APD linear arrays, which is a great improvement for 4H-SiC APD arrays. Moreover, the dark currents at 95% of breakdown voltage are below 1 nA for all the 64 pixels. Besides, the pixels in the array show a multiplication gain of larger than 10^6 and a peak responsivity of 0.12 A/W at 285 nm (corresponding to a maximum quantum efficiency of 52%) at room temperature.

Introduction: Silicon carbide (SiC) avalanche photodiodes (APDs) have been greatly investigated in recent years as the candidates for ultraviolet (UV) detectors to replace the conventional expensive, bulky and fragile photomultiplier tubes, which is of very importance in many applications such as flame detection, astronomical research, biochemical analysis and UV communication [1–10]. However, most of the previously reported works focus on the discrete device, while the research on 4H-SiC APD arrays is barely reported [11–14]. For some applications such as UV imaging and UV spectroscopy, 4H-SiC APD arrays are desired and will be one of the development trends for solid-state UV detectors. At present, the problem of fabricating 4H-SiC APD arrays is to achieve a high pixel yield, small variation of breakdown voltage (BV) and low dark current. The BV variation of early reported 4H-SiC APD arrays is larger than 2 V [11–13], which is unacceptable for practical applications. For the fabrication of 4H-SiC APD arrays, process variation must be considered and suppressed besides the growth of uniform low-defect-density 4H-SiC epitaxial material.

In this Letter, 1 × 64 linear arrays of 4H-SiC APD with high uniformity are reported for UV detection. In order to reduce the process variation, multi-cycle inductively coupled plasma (ICP) dry etching was adopted for the formation of bevelled mesa, during which the wafers are rotated with a small angle for each cycle process. As a result, the fabricated 1 × 64 linear arrays of 4H-SiC APD demonstrate a high pixel yield of 100% and a high uniformity of BV with a fluctuation of <0.5 V, which is a great improvement for 4H-SiC APD arrays. Besides, the dark currents at 95% of BV are all below 1 nA for the 64 pixels in the array. Moreover, the 4H-SiC APD pixels show a multiplication gain of $>10^6$ and a peak responsivity of 0.12 A/W at 285 nm at room temperature, corresponding to a maximum quantum efficiency (QE) of 52%.

Device design and fabrication: The 4H-SiC epi-layer structure in this work was carefully designed according to the work in [10]. Separate absorption charge multiplication epi-layer structure is used, as shown in Fig. 1*a*. Based on the chemical vapour deposition, the epitaxial layers were grown on an n-type low-defect-density substrate. From bottom to up, the wafer is composed of a 3 μm p^+ layer, a 0.5 μm n^- multiplication layer, a 0.2 μm n charge layer, a 0.5 μm n^- absorption layer and a 0.3 μm n^+ contact layer. The corresponding doping concentrations for the epi-layers are $N_a = 1 \times 10^{19}$ cm^{-3}, $N_d = 1 \times 10^{15}$ cm^{-3}, $N_d = 1 \times 10^{18}$ cm^{-3}, $N_d = 1 \times 10^{15}$ cm^{-3} and $N_d = 2 \times 10^{19}$ cm^{-3}, respectively. For fabrication of 1 × 64 4H-SiC APD linear arrays, the pixels were isolated with each other by positively bevelled mesa (angle = 8°). In order to reduce the process variation, an variable-temperature reflow technique in [9] and multi-cycle ICP dry etching was adopted for the bevelled mesa formation, during which the wafers were rotated with a small angle for each cycle etching process. The RF power and etching time of multi-cycle ICP are optimised with an etching cycle of 2 min for the mesa creation. After that, a metal stack with Ni (35 nm)/Ti (50 nm)/Al (150 nm)/Au (100 nm) was deposited by e-beam evaporation for contacts, which was followed by annealing at 800°C in N_2 ambient for 3 min. Then, the wafer was passivated by a high-quality SiN_x layer with a thickness of 500 nm, which was deposited by plasma enhanced chemical vapour deposition. With the passivation layer in the contact region removed, the metal stack for bonding pads was deposited with Ti (20 nm)/Au (200 nm). Finally, an optical window was opened by removing the SiN_x layer in the active region of pixels. The photo-image of part of the fabricated 1 × 64 4H-SiC APD array is shown in the inset of Fig. 1*b*. The diameters of the pixel and optical window are 200 and 140 μm, respectively, and the total length of the linear array is about 17 mm.

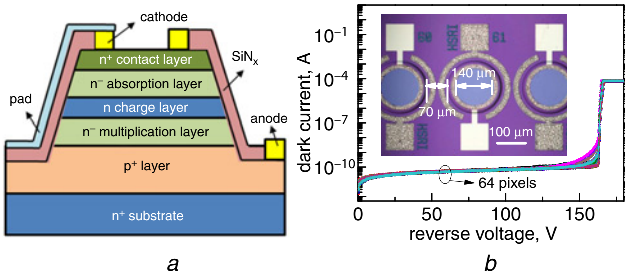

Fig. 1 *Structure of 1 × 64 4H-SiC APD linear arrays and I–V curves*

a Schematic cross-section structure of one 4H-SiC APD pixel
b Dark current versus reverse voltage with the photo-image of part of the linear array in the inset

Characterisation: As is known, it is difficult to achieve a high pixel yield with high uniformity of BV and low dark current for 4H-SiC APD arrays. First, the *I–V* characteristics without UV illumination were measured, and the reverse dark currents of all the pixels in the linear array are shown in Fig. 1*b*. It can be seen that all the 4H-SiC APD pixels in our fabricated 1 × 64 linear array show good hard avalanche breakdown, yielding a pixel field of 100%. In addition, the dark currents are very low at low reverse bias voltages for the pixels.

Furthermore, the UV detection performance is analysed for our 1 × 64 4H-SiC APD linear array. As shown in Fig. 2*a*, the dark current (I_{dark}) and photocurrent (I_{photo}) are plotted as a function of the reverse bias voltage, where the photocurrent was measured under UV illumination with $\lambda = 280$ nm. For simplicity, the results including the worst and best pixels in the array are chosen as examples to plot in Fig. 2*a*. By defining the multiplication gain as $M = (I_{photo} - I_{dark})/(I_{photo\_unity} - I_{dark\_unity})$, a high gain of $>10^6$ is achieved for the pixels with the unity gain at reverse voltage of 10 V. Moreover, the spectral response characteristics of the 4H-SiC APD pixels were measured from 200 to 400 nm at the reverse bias voltage of 10 V, as depicted in the inset of Fig. 2*a*. The responsivity has a peak of 0.12 A/W at 285 nm, corresponding to an external QE of 52%.

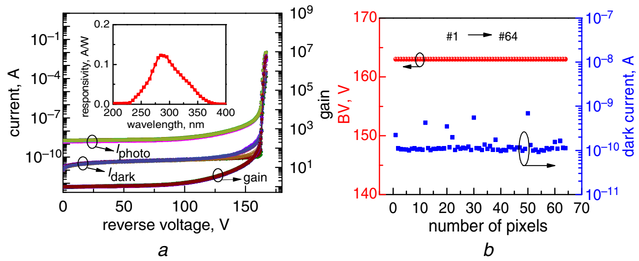

Fig. 2 *Performance of 1 × 64 4H-SiC APD linear array*

a UV detection performance of 4H-SiC APD pixels
b Profile of BV and dark current for 1 × 64 4H-SiC APD linear array

Finally, the uniformity of our 1 × 64 4H-SiC APD linear arrays with large-area pixels is investigated. Fig. 2*b* shows the profile of BV and dark current at 95% of BV for all the pixels. The results demonstrate that the BV is very uniform for all the APD pixels within the 1 × 64 linear array. A BV variation of <0.5 V is obtained for the pixels, which is much smaller than the BV variation of >2 V for other reported 4H-SiC APD arrays. Besides, the dark currents at 95% of BV are all below 1 nA for the 64 pixels in the array. The performance improvement of 4H-SiC APD linear arrays can be attributed to the low defect density of 4H-SiC epi-layers and the reduced process variation.

Conclusion: 1 × 64 4H-SiC APD linear arrays with high uniformity are reported in this Letter. It is demonstrated that multi-cycle ICP dry etching for the bevelled mesa can effectively reduce the process variation. As a result, the fabricated 1 × 64 linear arrays of 4H-SiC APD exhibit a high pixel yield of 100% and a high uniformity of BV with a fluctuation of <0.5 V, which is a great improvement for 4H-SiC APD arrays. Besides, the dark currents at 95% of BV are all below 1 nA for the 64 pixels. Moreover, the 4H-SiC APD pixels show a high multiplication gain of $>10^6$ and a maximum QE of 52%. The improvement of BV variation for 4H-SiC APD arrays will help to simplify the design of circuits for practical applications.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (grant no. 61974134).

Submitted: *03 May 2020* E-first: *22 June 2020*
doi: 10.1049/el.2020.1241
One or more of the Figures in this Letter are available in colour online.

Xingye Zhou, Xin Tan, Yuanjie Lv, Jia Li, Shixiong Liang, Zhihong Feng and Shujun Cai (*National Key Laboratory of ASIC, Hebei Semiconductor Research Institute, Shijiazhuang 050051, People's Republic of China*)

✉ E-mail: ga917vv@163.com

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