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Enhancement of operation temperature of InAs/GaAs quantum-dot infrared photodetectors with hydrogen-plasma treatment

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Postprocess hydrogen treatment is performed over fabricated ten-period InAs/GaAs quantum-dot infrared photodetectors. While keeping similar spectral responses at the same applied voltage, a reduced dark current is observed for the H-plasma-treated device, which is attributed to the suppression of surface leakage-current induced by surface damage during device processing. The significant reduction in dark current also enhanced the operation temperature of the device up to 100 K. Also observed are the smoothed-out mesa edges after the H-plasma treatment, which results in trapezoidal mesa edges. In this case, a longer propagation length in the device of the reflected incident light at the mesa edge would enhance the normal-incident absorption ratio of the H-plasma-treated device. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3196781]

I. INTRODUCTION

Quantum-dot infrared photodetectors (QDIPs) have attracted much attention in recent years due to their unique characteristics resulting from the three-dimensional confinement of the QD structures.[1–8] Two major advantages typically discussed of QDIP's compared with the conventional quantum-well infrared photodetectors (QWIPs) are high-temperature operation and insensitivity to incident-light polarization.[1–5] Although Ryzhii predicted low dark currents for QDIPs,[1] additional high-bandgap current-blocking layers are usually required for high-temperature operation.[2,3] The increased photocurrents with increasing temperature resulting from the reduced electron-capture probability are also reported to enhance the operation temperature of QDIPs.[4,5] Regarding the insensitivity of the device over incident-light polarization, due to the QD structures with zero volume in theory, the devices are not expected to obey the selection rule as in the case of QWIPs. Therefore, higher normal-incident absorption is expected for QDIPs. However, in the practical case, QD structures such as InAs grown on GaAs substrates usually exhibit a pyramid shape with <10 nm height and $40-50$ nm diameter. In this case, although higher normal-incident absorption is observed for QDIPs,[6,7] the normal-incident absorption ratio still depends strongly on the size of QD structures.[8] Therefore, to further enhance the device performance and normal-incident absorption of QDIPs, additional procedures should be considered for device fabrication.

In this article, postprocess hydrogen-plasma treatment is performed over a ten-period InAs/GaAs QDIP after device fabrication. While keeping similar spectral responses at the same applied voltage, reduced dark currents are observed for the H-plasma-treated device. The phenomenon is attributed to the suppression of the surface leakage current, which resulted from surface damage produced during the device-processing procedure. The significant dark-current reduction also enhanced the operation temperature of the device up to 100 K. Also observed are the smoothed-out mesa edges after the H-plasma treatment, which results in a longer propagation length in the device of the reflected incident light at the mesa edge. In this case, an enhanced normal-incident absorption ratio is observed for the device. The results suggest that hydrogen-plasma treatment is an efficient procedure for eliminating surface damage produced during device processing. The resulting trapezoidal mesa edges after H-plasma treatment are also helpful for fabricating QDIPs with corrugated structures to enhance the normal-incident absorption of the device.[9]

II. EXPERIMENT

The samples investigated in this article were grown on (100)-oriented semi-insulating GaAs substrates using a Riber

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TABLE I. Sample structures of ten-period QDIPs.

Top contact	300 nm GaAs $n=2\times10^{18}$ cm^{-3}
30 nm GaAs (ten times)	Undoped
2.4 ML InAs QDs (ten times)	Undoped
30 nm GaAs	Undoped
Bottom contact	600 nm GaAs $n=2\times10^{18}$ cm^{-3}
Substrate	350 μm (100) semi-insulating GaAs

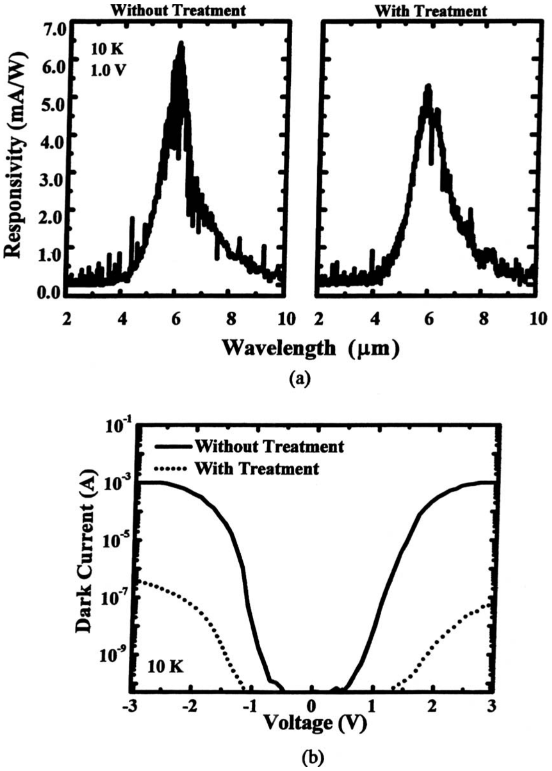

FIG. 1. (a) 10 K spectral responses at 1.0 V for the QDIPs with and without H-plasma treatment and (b) 10 K dark currents for both devices.

Compact 21 solid-source molecular-beam epitaxy (MBE) system. The device structure is shown in Table I. The active region consists of ten periods of 2.4 ML (monolayer) InAs QD layers separated by 30-nm-thick undoped GaAs barrier layers. 600 and 300 nm GaAs layers with $n=2\times10^{18}$ cm^{-3} were grown to sandwich the active region as the bottom- and top-contact layers. Standard photolithography and wet-chemical etching were adopted to fabricate the devices with 100×100 μm^2 mesas. A AuGe/Au alloy was deposited by metal evaporation to form Ohmic contacts after thermal annealing. After device fabrication, one sample was exposed under hydrogen plasma for 10 min, plasma power of 100 W, and hydrogen flow rate of 25 SCCM (SCCM denotes cubic centimeter per minute at STP). The spectral response for the devices with and without H-plasma treatment was measured under an edge-coupling scheme. For this purpose, the device was 45°-polished at one side of the sample. The infrared light source was normally incident to the polished surface. The positive and negative biases of the measurements were defined according to the voltages applied to the top contact of the device. The measurement system for spectral response consists of a Perkin Elmer Spectrum 100 Fourier transform infrared spectroscopy coupling with a Janis cryostat and current preamplifier. The current-voltage (*I-V*) characteristics were measured by a Keithley 236 source measure unit.[5–8]

III. RESULTS AND DISCUSSION

Figure 1(a) shows the 10 K spectral responses of the devices at 1.0 V with and without H-plasma treatment. As shown in this figure, no significant difference is observed for the two curves. Both devices exhibit broad detection wavelengths ranging from 4 to 9 μm with the same peak detection wavelength at ~6 μm. The results are frequently observed for the InAs/GaAs QDIPs prepared by MBE.[3–8] The 10 K dark currents of the two devices are shown in Fig. 1(b). There are two to three orders-of-magnitude reduction in dark current observed for the H-plasma treated device. Because wet-chemical etching is adopted for device fabrication, the phenomenon is attributed to the elimination of surface damage produced during device processing, and thus, leads to a much lower surface leakage current. The results also suggest that the surface leakage current is a dominant component of the dark current usually observed for QDIPs.

The detectives of the QDIPs with and without H-plasma treatment under different temperatures at 1.0 V are shown in Fig. 2. A high detectivity of 1.4×10^{10} cm Hz$^{1/2}$/W is observed for the device with H-plasma treatment at 10 K, which is one order of magnitude higher than the device without H-plasma treatment. The phenomenon is attributed to the reduced dark currents of the device with H-plasma treatment, as described previously. Also observed is the higher operation temperature of the device with H-plasma treatment at 1.0 V. For both devices, the photocurrents would increase with increasing temperature such that similar detectivity values are observed for each device under different temperatures.[4,5] However, due to the significant reduction in dark current for the device with H-plasma treatment, this device also shows a higher operation temperature of 100 K. The results suggest that the suppression of surface leakage current through H-plasma treatment would also enhance the operation temperature of the QDIPs.

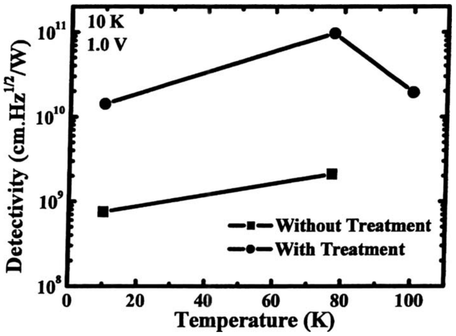

FIG. 2. Detectivities of the QDIPs with and without H-plasma treatment under different temperatures at 1.0 V.

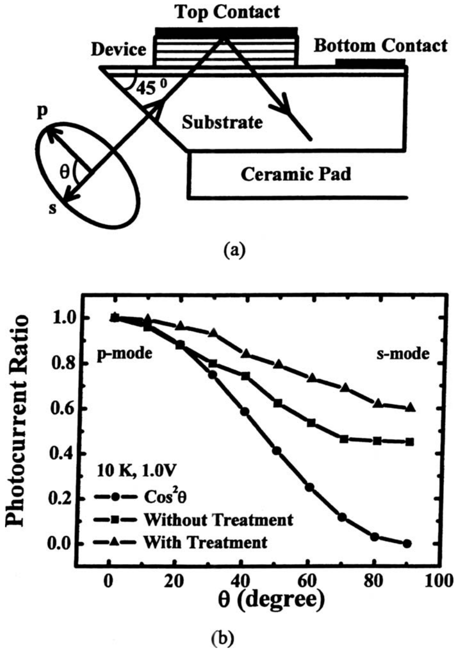

FIG. 3. (a) Measurement configuration and definition of incident-light polarization for the polarization-dependent responsivity for the QDIPs and (b) 10 K photocurrent ratios for the QDIPs with and without H-plasma treatment under different polarized angles away from the *p*-polarized light at 1.0 V bias.

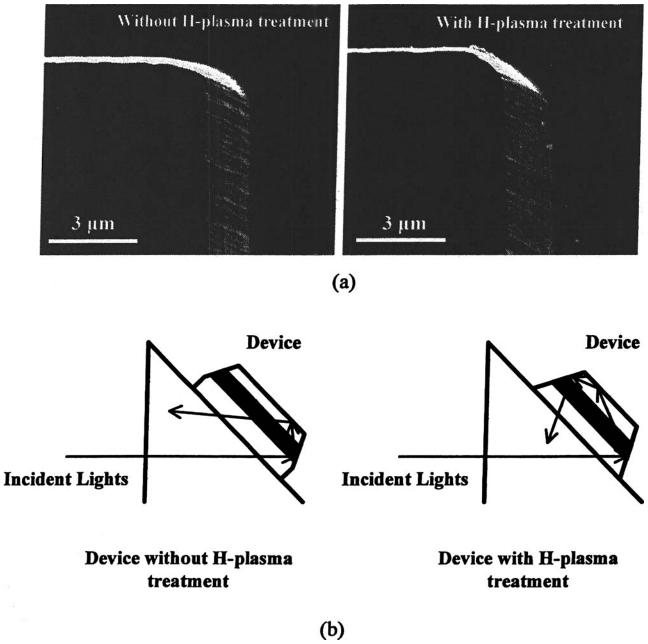

FIG. 4. (a) SEM images and (b) schematic ray diagrams for the incident light into the QDIPs with and without H-plasma treatment.

To investigate the influence of the H-plasma treatment on the normal-incident absorption of the QDIPs, responsivities of the devices under different infrared lights were measured. The measurement configuration for the polarization-dependent responsivity for the QDIPs is shown in Fig. 3(a). By changing the polarization of the incident light with a polarizer from *p*-to *s*-mode polarized light, it is possible to observe the polarization dependence of the devices. The 10 K photocurrent ratios of the devices as a function of polarized angle away from the *p*-polarized light at 1.0 V bias are shown in Fig. 3(b). The photocurrent ratio is defined as the photocurrent observed under different polarized lights of the devices divided by the photocurrent obtained under *p*-polarized light. The theoretically predicted curve following the $\cos^2 \theta$ rule for QWIPs is also shown in the figure as a reference.[10] As shown in the figure, photocurrent ratios of 0.45 and 0.6 are observed for the devices with and without H-plasma treatment, respectively. The results suggest that in addition to the dark-current suppression, H-plasma treatment could also enhance the normal-incident absorption ratio of the device.

We further investigate the mechanism responsible for the enhancement of normal-incident absorption of the QDIP after H-plasma treatment. The images observed by scanning electron microscop (SEM) for the devices before and after H-plasma treatment are shown in Fig. 4(a). An inspection of this figure reveals that two different slopes are observed at the sidewalls of the mesa for the device prior to H-plasma treatment. At the bottom of the etched mesa, a steep sidewall is observed, while a more flattened sidewall is shown near the top of the mesa. The steep sidewall of the mesa results from the vertical etching of the etchant, whereas the flattened sidewall results from the lateral etching underneath the photoresist. A rough surface is also revealed on the sidewall of the etched mesa. For the device after H-plasma treatment, the steep sidewall near the bottom of the mesa is smoothed out. Trapezoidal mesas with smoother sidewall surfaces can be obtained after the H-plasma treatment. To explain the contribution of trapezoidal mesas with smoother surfaces on the enhancement of the normal-incident absorption ratio of the device, the schematic ray diagrams of the incident light into the device are shown in Fig. 4(b). For the light incident to the mesa edges of the device without H-plasma treatment, the propagation length of the reflected light is quite limited within the device. However, for the device after the H-plasma treatment, the propagation length of reflected lights at the trapezoidal mesa edges is much longer within the device. Because most of the *p*-polarized light would be absorbed at the first or second time during the traveling of light through the active region, a longer propagation length of the *s*-mode light in the device would enhance the *s*-mode light absorption of the device. In this case, a higher photocurrent ratio for the *s*-mode light, as shown in Fig. 3(b), would be observed for the device with H-plasma treatment. The results suggest that H-plasma treatment is helpful for fabricating QDIPs with corrugated structures to further enhance their normal-incident absorption.[9]

IV. CONCLUSIONS

Hydrogen-plasma treatment is performed over a ten-period InAs/GaAs QDIP after device fabrication. With similar spectral responses at the same applied voltage, a reduced dark current is observed for the H-plasma-treated device. The phenomenon is attributed to the suppression of the surface leakage current, which resulted from surface damage produced during the device-processing procedure. The significant dark-current reduction also enhanced the operation temperature of the device up to 100 K. Also observed are the smoothed-out mesa edges after the H-plasma treatment, which results in a longer propagation length in the device of the reflected incident light at the mesa edge. In this case, an enhanced normal-incident absorption ratio is observed for the device. The results suggest that hydrogen-plasma treatment is an efficient method for eliminating surface damage produced during device processing. The resulting trapezoidal mesa edges after H-plasma treatment are also helpful for fabricating QDIPs with corrugated structures to enhance the normal-incident absorption of the QDIPs.

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