Surface leakage reduction in narrow band gap type-II antimonide-based superlattice photodiodes


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(Received 18 December 2008; accepted 14 January 2009; published online 3 February 2009)

Inductively coupled plasma (ICP) dry etching rendered structural and electrical enhancements on type-II antimonide-based superlattices compared to those delineated by electron cyclotron resonance (ECR) with a regenerative chemical wet etch. The surface resistivity of $4 \times 10^5 \ \Omega \ \text{cm}$ is evidence of the surface quality achieved with ICP etching and polyimide passivation. By only modifying the etching technique in the fabrication steps, the ICP-etched devices with a $9.3 \ \mu \text{m}$ cutoff wavelength revealed a diffusion-limited dark current density of $4.1 \times 10^{-6} \ \text{A/cm}^2$ and a maximum differential resistance at zero bias in excess of $5300 \ \Omega \ \text{cm}^2$ at $77 \ \text{K}$, which are an order of magnitude better in comparison to the ECR-etched devices. © 2009 American Institute of Physics. [DOI: 10.1063/1.3078282]
and trenches typically found in T2SL FPAs at the LWIR.

In order to compare these processes, devices were processed from a LWIR T2SL grown on a 2" residually p-type GaSb wafer in an Intevac Mod Gen II solid source molecular beam epitaxy system. The superlattice design was similar to that described in Ref. 3 with a total thickness of 7.7 μm, which previously attained QEs greater than 50% for top-side illumination and achieved background limited operation to 110 K, thanks to the device architecture and polyimide passivation. In this work, the reference sample (ECR-polyimide) was processed identically to the sample found in Ref. 3 with ECR etching and polyimide encapsulation. Compared to Ref. 3, the fluctuations in the indium growth rate caused the 50% cutoff wavelength to be shorter (9.3 μm) and also introduced a band discontinuity between the M-barrier and the standard T2SL, which is observed in the bias-dependent QE (Fig. 1 inset). Both can explain the slight improvement seen in the differential resistance at zero bias ($R_0A$) of ECR-polyimide (Table I).

Unlike the reference sample where a photoresist mask is used in ECR etching, a dielectric mask must be used in ICP etching. This is because the ions generated by the ICP system have higher energy and temperature. Under the bombardment of these hot ions, photoresist masks will cure and cannot be removed without using techniques that adversely affect the exposed T2SL sidewalls. It is noted that the device improvement shown between ICP and ECR-etched samples in Fig. 1 is not from the mask choice because no appreciable difference was seen in the sidewall morphology or the electrical performance of ECR-etched samples using either a photoresist or a dielectric mask. Another distinction between ECR and ICP-based processes is the post-citric-acid based wet etch that removed ECR-induced surface damage and residues by isotropically etching an additional 500 nm, while the ICP-etched sidewalls did not require further chemical treatment.

Following mesa delineation, all samples underwent solvent-based cleaning to ensure pristine sidewalls and were cleaved into 1×1 cm$^2$ dies to apply separate passivation. One die from each etching method was passivated with SiO$_2$ (ECR-SiO$_2$ and ICP-SiO$_2$) grown by plasma enhanced chemical vapor deposition (PECVD) and another was passivated with polyimide (ECR-polyimide and ICP-polyimide). To allow access to the Ti/Pt/Au Ohmic contacts, windows through the PECVD SiO$_2$ and polyimide layers were opened using CF$_4$ and O$_2$ plasma, respectively. Finally, the samples were mounted and the contacts were wire bonded to leadless chip carriers for electrical measurement.

To determine how the combination of etching and passivation affects the electrical performance, measurements were conducted at 77 K under 0° field of view conditions. The dark current densities of 320 μm diameter diodes are shown in Fig. 1 as a function of voltage and the electrical results are summarized in Table I for all four samples. The total dark current for each sample is a combination of the bulk current, which is common to all samples, and a surface component that is dependent on the surface treatment. In an ideal situation, the contribution of the surface should be minimal. Since ECR-polyimide achieved the lowest dark current and therefore the least amount of surface leakage, the samples that reveal a higher dark current level than ECR-polyimide are limited by stronger surface currents. ECR-polyimide’s low surface leakage can be attributed primarily to the pristine sidewall surface. In Fig. 1, ICP etching outperformed the ECR and wet-etching combination regardless of passivation technique, demonstrating that the limiting factor to bulk performance is the surface quality before passivation. Although wet etching greatly improves the device performance after ECR etching, it is possible that the wet etch step introduced additional surface traps on the sidewall. After mesa delineation, the physical protection of the sidewalls from ambient influences remains to be a crucial procedure. In the same figure, polyimide’s contribution to leakage current is shown to be consistently less than that of PECVD SiO$_2$ for both etching processes. It is believed that polyimide is closer to an electrically neutral passivation, which is desired to prevent further band bending from surface charge interactions. The ICP-polyimide combination provides a dark current density of 4.1×10$^{-6}$ A/cm$^2$, which is an order of magnitude lower than that of ECR-polyimide, and a maximum detectivity of 1.48×10$^{12}$ cm$^2$ Hz/W at a moderate 50 mV reverse bias.

The combined effects of etching and passivation shown in Fig. 1 are more apparent when the surface-to-bulk or perimeter-to-area (P/A) ratio is increased. Thus, an effective surface treatment technique will observe consistent current-voltage (I-V) behavior as diodes are varied by size. Since the square root of $R_0A$ is inversely proportional to Johnson-limited noise, it is more typical to plot ($R_0A$)$^{-1}$ rather than current density as a function of the P/A ratio (Fig. 2) to separate the bulk and surface contributions for diodes between 100 and 400 μm in diameter. In order to achieve the same $R_0A$ with varying P/A ratios, the sidewalls must block the passage of any carriers or show infinite resistivity (slope of zero). The relatively flat behavior of ICP-polyimide verifies its high sidewall resistivity, which was calculated from the inverse of the slope to be $4×10^5$ Ω cm. In comparison

![FIG. 1. (Color online) The dark current densities ($j_0$) of 320 μm diameter diodes measured at 77 K are shown for all samples. An improvement in the ICP-etched sidewall surface quality is revealed by their lower $j_0$, regardless of passivation technique. The bias-dependent QE is shown in the inset.](image-url)
to ICP-polyimide, ECR-polyimide had a surface resistivity of $6.7 \times 10^6$ $\Omega$ cm, which confirms the role that ICP etching has on reducing surface leakage by achieving better surface conditions before passivation.

An alternative method to observe surface-related leakage is through temperature-dependent measurements of the dark current. The dark current densities at 50 mV reverse bias are shown as a function of inverse temperature in Fig. 3 for different sized ICP-etched diodes. The diodes exhibited an Arrhenius-type behavior above 100 K, which is a clear indication that the dominant mechanism is the bulk diffusion current. At lower temperatures, the current begins to deviate from this trend. Contrary to the analysis in Ref. 13, the saturation of the dark current in this case is not due to bulk generation recombination or tunneling, but comes from the presence of surface leakage since the dark currents for two distinctly sized diodes from the same die saturate at different levels (Fig. 3). The onset of surface leakage, as seen by the deviation from the bulk diffusion trend, occurred at 77 K for ICP-polyimide ($320 \mu$m in diameter), while the onset temperature was higher for the other samples. ECR-etched samples are omitted from this figure since they saturate at higher current densities. Below 77 K, ICP-polyimide continued to have a decreasing dark current with temperature, reaching $7 \times 10^{-8}$ A/cm$^2$ at 20 K (not shown) while ICP-SiO$_2$ remains temperature invariant. This indicates that the polyimide passivation contributes fewer surface trap states, while PECVD SiO$_2$ appears to reach a threshold preventing the dark current from decreasing further. The decreasing dark current seen in ICP-polyimide caused its $100 \mu$m diode to eventually outperform the $320 \mu$m ICP-SiO$_2$ diode for temperatures below 50 K. By decreasing the operational temperature, further improvements in noise performance are possible for small devices such as those found in FPAs.

In summary, improvements to the surface are necessary to reduce surface leakage current in order to reach the intended bulk performance of high quality T2SLs at the LWIR. The surface condition prior to passivation has been identified as a main source of leakage and can limit the effect of passivation. By using ICP dry etching alone as an alternative to the ECR and wet etch combination, the dark current density and surface resistivity improved by an order of magnitude and five times, respectively. These performance enhancements attest to the fact that T2SLs based on ICP mesa delineation can be seen as a viable option for third generation imaging systems.

The authors would like to thank our collaborators Dr. Fenner Milton and Dr. Joe Pellegrino from the U.S. Army Night Vision & Electronic Sensors Directorate and Dr. Meimei Tidrow from the Missile Defense Agency.


FIG. 2. (Color online) The inverse $R_p A$ is shown as a function of $P/A$ for diodes between 100 and 400 $\mu$m in diameter at 77 K. The high surface resistivity of ICP-polyimide is revealed by its near zero slope. The inset equation is used to extract surface resistivity.

FIG. 3. (Color online) Dark current density temperature dependent measurements of 320 and 100 $\mu$m diameter diodes for the ICP-etched samples are shown at 50 mV reverse bias. Since the samples vary only in processing technique, deviation from the bulk diffusion trend for each curve indicates the onset of surface leakage.