

LATERAL p-i-n PHOTODETECTORS WITH 18 GHz BANDWIDTH AT 1.3 μm WAVELENGTH AND SMALL BIAS VOLTAGES

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Abstract

Simultaneous n-type and p-type diffusion, compositional mixing, and formation of ohmic contacts, have been employed in the fabrication of lateral p-i-n photodetectors for short (0.85 μm) and long (1.3 μm and 1.5 μm) wavelengths. Zinc-doped tungsten (W(Zn)) and MoGe_2 are employed for the p-type and n-type contacts, doping, and compositional mixing using rapid thermal processing at $\approx 750^\circ\text{C}$. With structures utilizing GaAs and $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ active regions, 3-dB bandwidths exceeding 7.5 GHz and 18.0 GHz respectively, have been achieved at bias voltages of $\approx 5\text{ V}$. The corresponding dark currents are sub-100 pA and sub-10 nA and the devices exhibit a large dynamic range, near-ideal responsivity, and a high sensitivity. The performance, ease of fabrication, and process compatibility make these devices suitable for integration in digital circuits employing field effect transistors.

Introduction

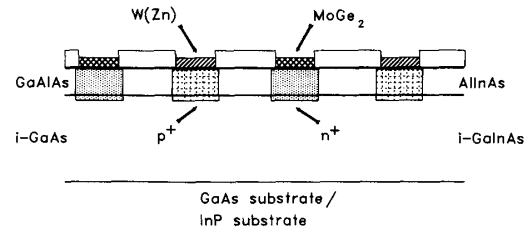
Present day digital optical communication circuits are largely based on vertical p-i-n photodetectors because of their high sensitivity, large dynamic range, low dark currents, large bandwidths, and ease of fabrication. Such circuits, however, utilize hybrid technology because of difficulties in integrating vertical detectors with planar transistors and other circuit components. Monolithic integration of the vertical p-i-n structures requires shortening of the active region to limit the non-planarity of the surface. This has to be accomplished without a significant change in the cross-section area of the device which is determined by requirements of coupling to a fiber. Therefore, the short active region in a monolithically integratable vertical structure results in a higher capacitance and poorer bandwidth. Metal-semiconductor-metal (m-s-m) photodetectors [1,2], formed as lateral structures, have been explored and utilized as an alternative for monolithic integration. 3-dB bandwidths in the 5-10 GHz range have been achieved in these structures at bias voltages of $\approx 10\text{ V}$ and higher. The bandwidth and bias limitations of m-s-m structures arise from hole storage and hole transport effects due to the use of an abrupt-interface larger bandgap material at the surface (e.g., $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$) in order to reduce dark currents. One of the major advantages of p-i-n structures is the efficient collection of both carriers with the use of reversed biased graded semiconductor homojunctions or heterojunctions. p-i-n structures, therefore, do not exhibit hole storage effects.

The problem of larger capacitance of vertical monolithic p-i-n structures can be alleviated by the use of a lateral geometry p-i-n structure [3,4]. Earlier reports [3,4] utilized homojunctions in GaAs and a non-self-aligned technology based on implantation and AuGe contacts. Reference [4] demonstrated a p-i-n/FET receiver with $\pm 3\text{ dB}$ response in the 2–4 GHz range. Here, we report a significant extension of the performance and the use of $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ and heterostructures with a self-aligned doping and contacting process that allows for heterojunction grading in the contact regions. The tech-

niques employed are compatible with heterostructure and homostructure field effect transistors and should allow receiver bandwidths to be extendable to $\approx 20\text{ GHz}$ employing digital power supply voltages.

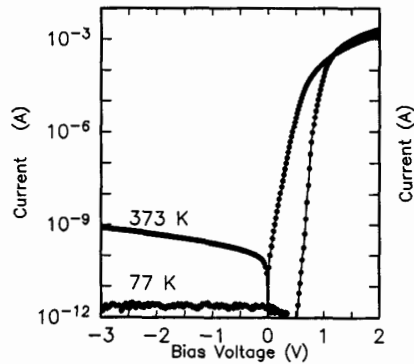
Device Fabrication

The schematic geometry of the structures reported here is shown in Fig. 1. Undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ or $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$, where the larger bandgap material serves as a surface barrier layer and the smaller bandgap material serves as the active carrier generation layer, are grown with thicknesses compatible with the insulator-gate heterostructure field effect transistors (HIFETs) or heterostructure metal-semiconductor field effect transistors (HMESFETs). GaAs MESFETs can be fabricated by removing the barrier layer. For improvement of the material quality and reduction in trap-assisted carrier generation-recombination processes, the underlying layers of this structure can consist of superlattices that may also be designed for maximum reflection.

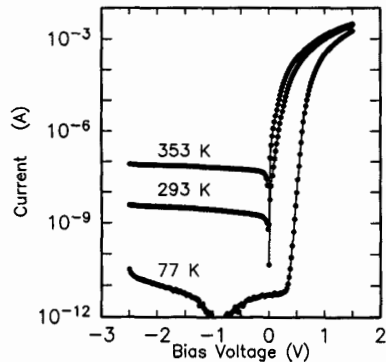


1. A schematic of the lateral p-i-n device structure.

The p-type and n-type collection regions are formed by diffusion from metal films that also form the ohmic contact. The p-type region utilizes a Zn-doped W film [5] and the n-type region utilizes MoGe_2 [6]. During and after diffusion, a layer of silicon nitride serves as a diffusion barrier and insulating layer for interconnections. Using rapid thermal processing at $700\text{--}750^\circ\text{C}$ for 30–60 s, p- and n-type diffusion depths of less than 1000 Å are obtained. The diffusion of zinc and germanium, during the rapid thermal process, causes a doping of $\approx 10^{20}\text{ cm}^{-3}$ p-type and high- 10^{19} cm^{-3} n-type. These result in the simultaneous formation of p-type and n-type ohmic contacts. The diffusion also has another device-related attribute. The diffusion of zinc and germanium involves group III lattice sites. This results in compositional mixing in the regions under the contact and in grading of the previously abrupt barriers. Compositional mixing resulting from diffusion of zinc from a vapor source [7] is now well documented, although the underlying theoretical basis for compositional mixing is subject to some debate since during diffusion most of the zinc is at interstitial sites [8,9]. Here, we have adopted a metal-based film that also forms a self-aligned ohmic contact. However, the features related



2. Current-voltage characteristics at 77 K and 373 K for a $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}/\text{GaAs}$ p-i-n structure. The device has $2\text{ }\mu\text{m}$ finger length, $90\text{ }\mu\text{m}$ finger width, $1\text{ }\mu\text{m}$ finger spacing, and 8 fingers of p-type and n-type contacts.

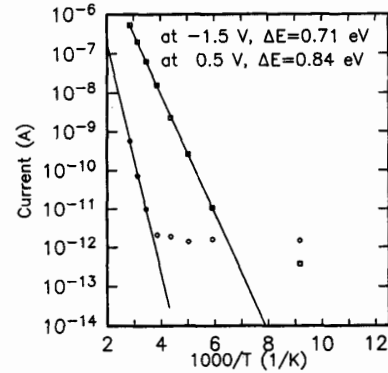


3. Current-voltage characteristics between 77 K and 353 K for an $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ p-i-n structure. The device has $2\text{ }\mu\text{m}$ finger length, $90\text{ }\mu\text{m}$ finger width, $1\text{ }\mu\text{m}$ finger spacing, and 8 fingers of p-type and n-type contacts.

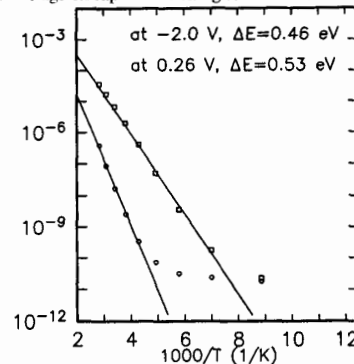
to compositional mixing from a vapor source are maintained since the mechanisms of diffusion, involving the group III lattice sites, are expected to be similar. The compositional mixing resulting from diffusion of germanium is also expected to be similar to that due to diffusion of silicon. The latter has been effectively employed in fabrication of electronic and optical device structures [10,11]. The use of MoGe_2 results in enhanced diffusion of germanium to the desired diffusion depths at time scales compatible with rapid thermal processing and abrupt heterostructure field effect transistor fabrication.

Results and Discussion

The dark current-voltage characteristics for GaAs and $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ active regions, i.e., for short and long wavelength structures, are shown in Fig. 2 and 3 for a broad temperature range between 77 K and $\geq 353\text{ K}$. The dimensions of the device structures are indicated in the captions of the figures. The dark currents in the short wavelength structures remain below a nA and those for long wavelength structures remain below 100 nA over the temperature range shown. These are similar to the best results reported on m-s-m structures and indicate preservation of junction quality during the self-aligned diffusion process. To ascertain the underlying mechanism of this current, Fig. 4 and 5 show the activation energy plots for reverse and forward currents of representative p-i-n structures. The activation energies exceed half of the bandgap, indicating appreciable generation-recombination effects; this is not unexpected in a p-i-n structure which



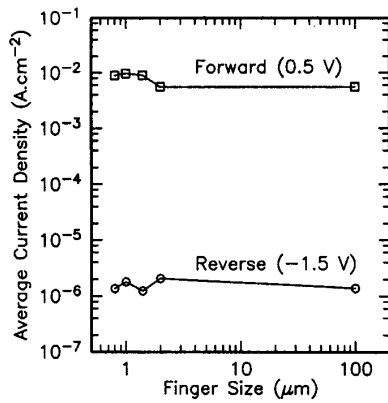
Current at a reverse bias of 1.5 V (circles) and forward bias of 0.5 V (squares) as a function of the inverse of the temperature for a representative $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}/\text{GaAs}$ p-i-n structure. The activation energy in forward bias and reverse bias correspond to zero-voltage extrapolation energies of 0.71 eV and 0.84 eV.



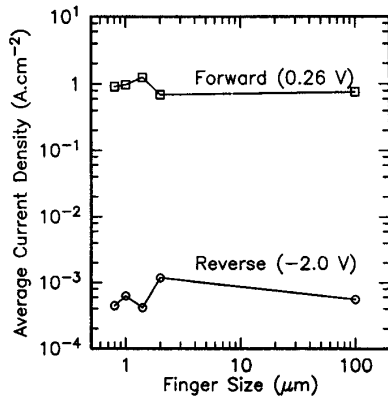
Current at a reverse bias of 2.0 V (circles) and forward bias of 0.26 V (squares) as a function of the inverse of the temperature for a representative $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ p-i-n structure. The activation energy in reverse bias and forward bias correspond to zero-voltage extrapolation energies of 0.46 eV and 0.53 eV.

contains a large region for bulk generation-recombination processes. However, this activation energy can also arise from surface effects. We verify that this is not the case by measuring the current densities, in forward and reverse bias, for varying finger sizes, i.e., with varying perimeters. Fig. 6 and 7 show absence of a clear correlation between perimeter and current density. Thus, the large bandgap surface barrier layer appears to be effective in reducing surface recombination and the transport in the structures is dominated by bulk effects with lifetimes exceeding a μs . These lifetimes are of the same order as obtained in the as-grown material. The large built-in voltage, which is close to the bandgap, and the suppression of perimeter effects, allow the low dark currents obtained in these structures. Unlike p-type implantation-based [3] or AuGe-contact based [4] structures, the use of diffusion allows a large lifetime to be retained. It also allows for a self-aligned structure with a corresponding simplification in the process.

For both short and long wavelength devices, with finger spacings between $1.0\text{ }\mu\text{m}$ and $4.0\text{ }\mu\text{m}$, the bandwidths rise rapidly for bias voltages between 1.5 V and 3.5 V. Direct bandwidth measurements, using an apparatus limited to 3–4 GHz, are shown in Fig. 8 for the long wavelength structure at two different finger spacings. The points in excess of 3 GHz should be discounted due to the limitations of system resolution but this figure serves to show that even relatively large finger



6. Current density at a reverse bias of 1.5 V and forward bias of 0.5 V as a function of the finger size for representative $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}/\text{GaAs}$ p-i-n structures.

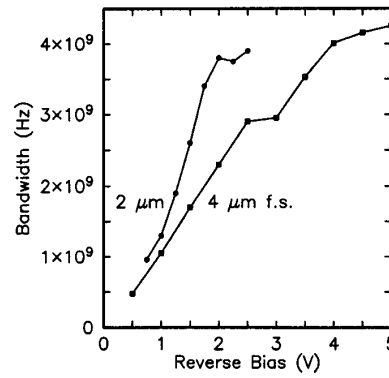


7. Current density at a reverse bias of 2.0 V and forward bias of 0.26 V as a function of the finger size for representative $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ p-i-n structures.

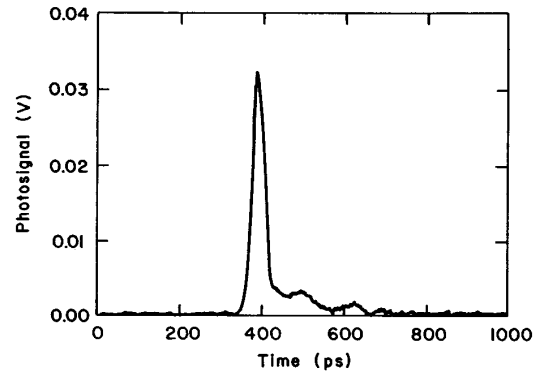
spacings of $4\text{ }\mu\text{m}$ are sufficient to obtain $\geq 4\text{ GHz}$ bandwidth at bias voltages of 4 V.

Temporal measurements allow us to determine the bandwidths more accurately using Fourier transformation. For the structure of Fig. 8, they exceed 5 GHz at both finger spacings at $\approx 3.5\text{ V}$ bias and for the shorter finger spacing they saturate at a reverse bias below 7.5 V. Bandwidths exceeding 7.5 GHz and 18.0 GHz respectively have been obtained using the short wavelength and long wavelength structures at $\approx 5\text{ V}$ bias. Figures 9 and 10 show the temporal response and the de-convolved frequency response for a long wavelength detector. This device has a finger length of $1.4\text{ }\mu\text{m}$, a spacing of $2\text{ }\mu\text{m}$, and has 3 fingers of $20\text{ }\mu\text{m}$ width each. The full width at half maximum (FWHM) ranges between 31 and 35 ps for 3 to 6 V bias voltage for this structure, and is largely dominated by the pulse and probe time constants estimated to be $\approx 15\text{ ps}$ each. The latter have been extracted in the de-convoluted data of current response shown in Fig. 10. The 3-dB bandwidth for this example exceeds 18 GHz. The structures also do not exhibit excess long time constant tails, usually observed in m-s-m structures, at bias voltages exceeding 1.5 V. The tails of Fig. 9 are dominated by the non-idealities of the measurement system—reflections and secondary pulses from the laser.

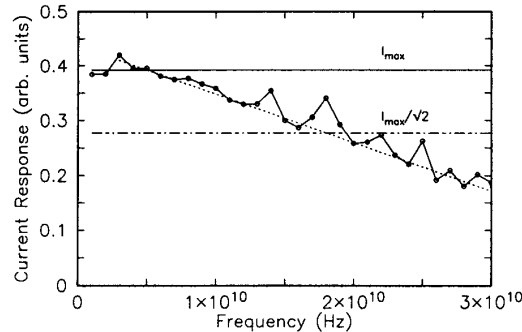
As compared to m-s-m structures, the attractive dynamic attributes of the p-i-n structures are believed to result partly from compositional mixing of the abrupt interface together with the ability to form an acceptable ohmic contact. Fig. 11 shows a surface plot, at thermal equilibrium, of the conduction band edge in the region between two cross-sections through the n-type and p-type contact regions and going into the substrate. The compositional mixing and doping removes or reduces the barrier to flow of carriers, allowing for efficient collection of both electrons and holes. p-i-n structures also have a large built-in electric field because of the larger built-in potential. Fig. 11 shows the



8. Directly measured 3-dB bandwidth for $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ p-i-n structures of $2\text{ }\mu\text{m}$ and $4\text{ }\mu\text{m}$ finger spacing. The system resolution is 3 GHz.

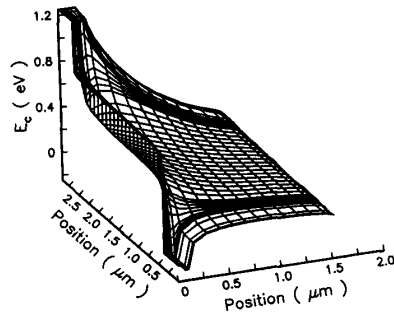


9. Temporal response of the $\text{Ga}_{0.48}\text{In}_{0.52}\text{As}$ p-i-n structure. The finger spacing is $2\text{ }\mu\text{m}$ and the device has 3 p- and n-type fingers which are $20\text{ }\mu\text{m}$ wide.

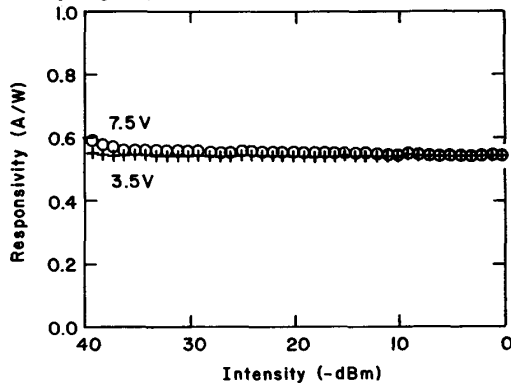


10. De-embedded frequency response using Fourier transform of the temporal response for the $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ photodetector. The finger spacing is $2\text{ }\mu\text{m}$ and the device has 3 p- and n-type fingers which are $20\text{ }\mu\text{m}$ wide.

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11. Surface plot of the conduction band edge, for a $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}/\text{GaAs}$ p-i-n structure, plotted between the n-type and p-type contact and going into the substrate. The finger spacing is $2\text{ }\mu\text{m}$.



12. The responsivity of an $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ photodetector as a function of light intensity.

existence of this built-in field for both electrons and holes. This field allows for larger carrier velocities to be achieved at small bias voltages. Thus, the efficient transport and collection allows for larger bandwidths at smaller bias voltages than a comparable m-s-m structure. The compositional mixing also substantially reduces the long time constant tails in the temporal response and the low-frequency gain. For example, the leakage current, with illumination, is estimated to increase only by 5 nA at 7.5 V in the long wavelength devices. These voltages, unlike other reports of large bandwidth detector structures, are now compatible with power supply voltages of digital circuits.

The structures, as expected, exhibit large responsivities as well as large dynamic range. The responsivity of a long wavelength structure ($\sim 0.53\text{ A/W}$) is shown in Fig. 12. This responsivity corresponds to $\approx 95\%$ internal quantum efficiency and originates both in the efficient collection as well as the unintentional reflectivity of an underlying $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ buffer layer. The dynamic range and nearly-flat and bias-independent response of the responsivity is a particularly important attribute of these structures. This behavior results largely from the compositional mixing and doping that allows for efficient collection and the large built-in fields that allow for efficient transport at small bias voltages.

Microwave measurements, in the absence of illumination, show that the capacitances of the structures at zero bias are slightly larger than those of the corresponding m-s-m structures. For a structure with 8 fingers of $2\text{ }\mu\text{m}$ length and $90\text{ }\mu\text{m}$ width that are spaced $2\text{ }\mu\text{m}$ apart, the zero bias capacitance is $\approx 150\text{ fF}$ and reduces to $\approx 80\text{ fF}$ at 5 V reverse bias. The additional capacitance inherent in a lateral p-i-n

structure appears to be small due to the larger built-in voltages, compared to m-s-m structures.

The large bandwidths achieved in these devices exceed the requirements of present optoelectronic circuits. However, a particular advantage accrued from these large bandwidths at small biases, a high responsivity, and a large dynamic range, is the ability to trade-off these features to obtain a detector with a very relaxed geometry but still exhibiting high sensitivity and large bandwidths at voltages that are desired in digital circuits. Thus, the techniques presented here should still be of interest in optoelectronic circuits at lower frequencies and speed.

Conclusions

We have developed a method for fabricating nearly-ideal lateral p-i-n photodetectors for both long and short wavelengths. These detectors utilize voltages that are compatible with digital circuits and utilize material structures that are compatible with heterostructure-based FET technologies and with MESFET technologies. The structures are similar to m-s-m structures and require one or two additional mask alignments. These devices permit the use of lower bias voltages by achieving efficient collection of electrons and holes. Additionally, this bias advantage can be traded for higher sensitivity by utilizing larger finger spacings.

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