HTML ABSTRACT + LINKS

Photomixers fabricated on nitrogen-ion-implanted GaAs

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We report on fabrication and measurement of photomixers based on nitrogen-ion-implanted GaAs. We used energies of 500 keV, 700 keV, and 880 keV to implant N^+ ions into GaAs substrates with an ion concentration of $\sim 3\times 10^{12}$ cm^{-2}. The resulting material exhibited 110 fs carrier lifetime due to implantation-induced defects. Our photomixers were fabricated as metal-semiconductor-metal devices, placed at the feed point of a broadband antenna. Optoelectronic measurements were performed in the wavelength range between 350 nm and 950 nm. In comparison to their counterparts (photomixers fabricated on low-temperature-grown GaAs) the N^+-implanted GaAs photomixers exhibit improvements on both the output power and responsivity. A maximal responsivity of above 100 mA/W was achieved and we did not observe any dependence of the mixer cut-off frequency on the bias voltage. These characteristics make N^+-implanted GaAs the material of choice for efficient optoelectronic photomixers. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2006983]

Ion implantation is well known to reduce carrier lifetime in GaAs-based photodetectors. Values in the picosecond and even subpicosecond regime have been reported in the past. The properties of GaAs implanted with protons,[1] Ar^+,[2,3] As^+,[4–6] and other ions have been extensively investigated. The implantation of nitrogen ions in GaAs, however, is relatively new. The initial objective of implanting N ions in GaAs was to get the diluted ternary semiconductor GaAsN. The optical properties of this new material, such as photoluminescence[7] and N^+-induced band-gap reduction,[8] have been studied in previous works. It is also noted that high-energy N^+-implanted GaAs becomes a highly resistive material after high-temperature annealing.[9,10]

In a previous work, we have presented ultrafast photodetectors based on N^+-implanted GaAs with increased responsivity and very low dark currents.[11] The purpose of this letter is to describe the fabrication process, as well as the properties of photomixers fabricated using high energy N^+-implanted GaAs substrates. Furthermore, we present a performance improvement of these photomixers, as to the devices fabricated on low-temperature-grown GaAs (LT-GaAs).[12–14]

The fabrication process started with implantation of N ions with energies of 500 keV, 700 keV, and 880 keV, respectively, into 2 μm thick, 10^{17} cm^{-3} *n*-doped GaAs layers grown by molecular-beam epitaxy on semi-insulating GaAs (001) substrates. The implantation was performed by the linear, 900 kV accelerator at the Slovak University of Technology, Bratislava, Slovakia. For all samples, the ion dose was about 3×10^{12} cm^{-2}. The depth of the implantation maximum was about 800 nm, 1000 nm, and 1200 nm for the 500, 700, and 880 keV implantation energies, respectively.[11,15] Next, metal-semiconductor-metal (MSM) structures with an active area of 100 μm^2 and finger width and spacing of 1 μm and 1.5 μm, respectively, were patterned on the N^+-implanted GaAs materials using conventional photolithography and lift-off technique.[10,11] The MSM structures consisted of Ti/Au contacts with 10/160 nm thicknesses. For comparison, an MSM structure with the same geometry as above was fabricated on LT-GaAs. After fabrication of the MSM structures, their whole surface was coated with 200 nm of SiO_2 and the windows were opened in the SiO_2 layer to contact the MSM electrodes. Ti/Au bow-tie anten-

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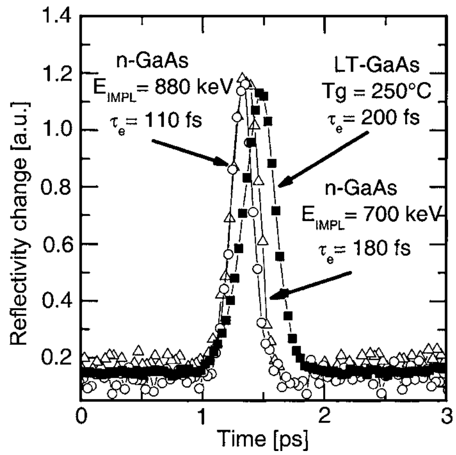

FIG. 1. Carrier lifetimes in LT-GaAs (growth temperature T_g=250 °C) and in N^+-implanted GaAs implanted with energies 700 keV and 880 keV, obtained from the normalized optical reflectivity change measured using femtosecond pump/probe spectroscopy.

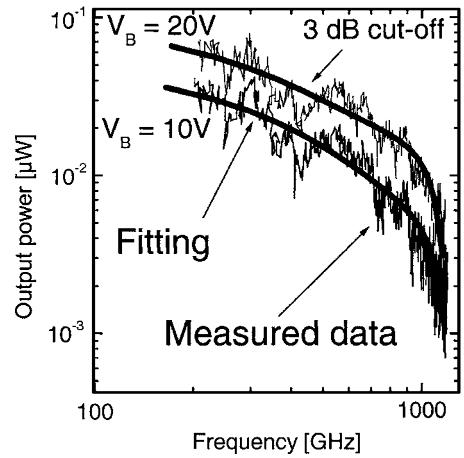

FIG. 3. Output power (thin lines) for a photomixer fabricated on N^+-implanted GaAs as a function of the intermediate frequency, measured for 780 nm wavelength, 70–80 mW input power optical radiation for two bias levels (10 V and 20 V). Implantation energy is 880 keV. Bold solid lines correspond to a polynomial fit as a guide for the eyes.

nas with thicknesses of 50/600 nm were fabricated on the top of the SiO_2 insulator layer.

The lifetime of the photogenerated carriers in N^+-implanted GaAs and LT-GaAs was studied using femtosecond time-resolved reflectivity measurements by an all-optical pump/probe system featuring ~70 fs temporal resolution. Carrier lifetimes of less than 200 fs were obtained for the samples implanted with energies in the range from 500 keV up to 880 keV.[10] Figure 1 shows our experimental pump/probe results for both N^+-implanted GaAs and LT-GaAs. We note that the material implanted with 880 keV energy exhibits a carrier lifetime of only 110 fs, which is almost 50% shorter than the value measured for LT-GaAs. Significantly shorter carrier lifetime translates in wider bandwidth and better THz efficiency of the photomixers based on N^+-implanted GaAs, as compared to those based on LT-GaAs.[12] The other very important feature of photomixers is their as high as possible photocurrent, or high responsivity, in order to assure the highest possible output power. The photodetectors based on N^+-implanted GaAs exhibit more than twice the responsivity when compared to LT-GaAs devices, as was demonstrated in our previous works.[10,11]

Figure 2 depicts the results of our spectral responsivity measurements performed with MSM photodetectors based on N^+-implanted GaAs and compared with those based on LT-GaAs. The spectral measurements were performed with a setup where the light from a xenon arc lamp is directed through a grating monochromator. The monochromatic light is focused by a lens to the device under test. The measurement accuracy is improved by a lock-in amplifier including a chopper in the light beam. The responsivity increases with a decrease of the implantation energy. This dependence is due to the shorter implantation depth for lower energies. In this case, a higher amount of photons penetrates the nonmodified bulk material with larger carrier lifetime. The photoconductor gain and therefore the responsivity are proportional to the lifetime of the photogenerated carriers, resulting in the higher responsivity for the lower energy devices. Figure 2 also shows that the responsivity of photodetectors based on the implanted material increases at shorter wavelengths, in contrast to the results obtained for LT-GaAs. We explain this behavior by the smaller penetration depth of the short-wavelength light. It decreases from 1 μm at 850 nm wavelength to 100 nm at 500 nm wavelength.[16] A larger amount of the photocurrent is then generated near the surface where the defect density is smaller, giving a larger quantum efficiency. This increase of the quantum efficiency with decreasing wavelength compensates for the usual linear dependence of the responsivity on wavelength.

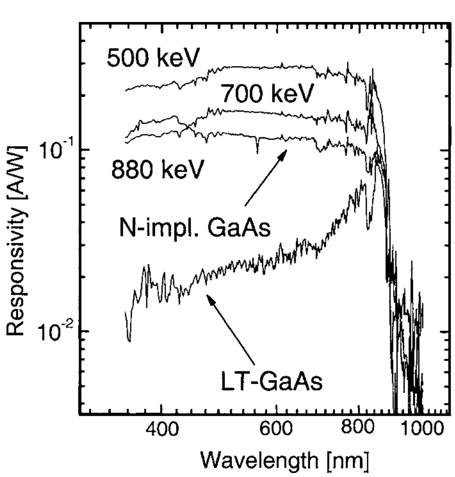

FIG. 2. Spectral responsivity characteristics for photomixers fabricated on LT-GaAs and N^+-implanted GaAs materials, measured at 10 V bias voltage.

Photomixing measurements were performed in a heterodyne photomixer setup with 780-nm-wavelength continuous-wave radiation from two solid-state lasers.[17] Experimental data shown in Fig. 3 demonstrate that devices on N^+-implanted GaAs can indeed, very efficiently, generate THz radiation. The output power depends on the bias voltage, as it was expected by the voltage-dependent responsivity of photoconductors[11] and reached 13 nW at 1 THz at the bias voltage of 20 V. The fitting curve corresponds to a polynomial fit as a guide for the eyes. The gradual rolloff between 100 and 1000 GHz and the faster roll-off above 1 THz in the input power is due to the two low-pass contributions by carrier lifetime and resistance/capacitance time constant.[12] A further increase of the output power could be obtained by the optimization of the photodetector design to a smaller active area with sub-μm MSM finger widths, and by using a dipole-type instead of the bow-tie-type THz antenna.

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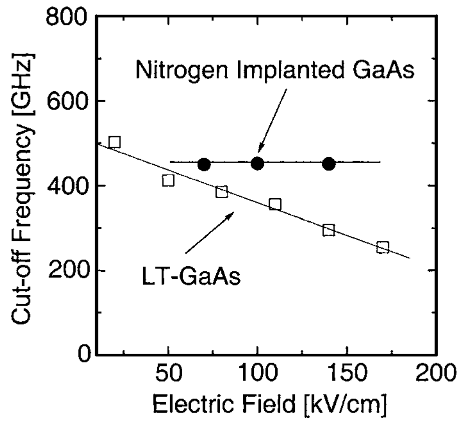

FIG. 4. The cut-off frequency dependencies as a function of the applied electric field for N^+-implanted GaAs (implantation energy: 880 keV; closed circles) and LT-GaAs (open squares) photomixers.

Finally, Fig. 4 shows the dependence of the cut-off frequency (3 dB drop from the low-frequency value) of our N^+-implanted GaAs photomixers on the average electric field defined as the ration of applied bias to MSM finger spacing, again, in comparison with LT-GaAs devices. It should be noted that the effective electric field in the depth of the implantation maximum decreases to about 15% of the above mentioned average value.[18] For the LT-GaAs photomixers, the cut-off frequency decreases rapidly with the increase of the applied electric field, while in the case of the N^+-implanted GaAs photomixers the cut-off frequency does not depend on the applied bias and remains constant in the whole range of tested electric fields (between 50 and 200 kV/cm). The behavior observed in the LT-GaAs devices is typical for their performance and indicates a reduction of the electron capture cross section with the increased electric field, as was observed earlier by Zamdmer and Hu.[19] Our N^+-implanted GaAs photomixers are clearly free of the problem of the rf power saturation with increasing bias. We attribute this superior behavior of the implanted material to the different, as compared to LT-GaAs, physical origin of the implantation defects that act as carrier traps.

We have fabricated THz bandwidth photomixers based on N^+-implanted GaAs. The different origin of the carrier traps, formed during the implantation process, as compared to As precipitates on LT-GaAs lead to the novel material with ultrashort carrier lifetime and, simultaneously, increased responsivity, leading to the very good performance of photomixers fabricated on the implanted material. As compared to photomixers fabricated on LT-GaAs, our devices show higher cut-off frequencies for electric fields in the range from 50 to 200 kV/cm. Simultaneously, the value of the cut-off frequency is independent of the bias voltage, which eliminates the problem of the rf output power saturation, typical for the LT-GaAs-based photomixers. A further improvement of the device performance is expected by the fine-tuned optimization of the implantation dose and energy of the nitrogen ions and by fabrication of MSM structures with submicrometer dimensions.

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