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Annotation

Doping with isovalent impurities can serve as one of the methods for modifying III–V semiconductors. Of interest is the doping of GaAs with Bi atoms, which are isovalent to As. Bismuth atoms are heavier than arsenic atoms, so doping with Bi of gallium arsenide leads to a significant change of its properties. It was shown in a literature that the introduction of bismuth leads to a significant decrease in the band [1] and also affects the gap electrotransport properties [2]. As an alternative to the epitaxial methods of obtaining GaAs:Bi, which are usually described in the literature, we use bismuth doping by ion implantation in this work.

Experimental technique

Bismuth ions were implanted into i-GaAs(001) at the «Радуга – 3М» accelerator, while the accelerating voltage and the dose of implanted ions were varied. The main feature of the accelerator is a vacuum arc source, which makes it possible to create intense ion beams using metallic solid starting materials. The source operates in a repetitively pulsed mode with a pulse duration of $\approx 200 \ \mu s$ and a repetition rate of 10–20 pulses/s. Another feature of the accelerator is that the ion beam contains several charge fractions, and the distribution over fractions depends on the specific metal [3]. After implantation, one part of the samples was subjected to pulsed laser annealing (LA) by an excimer KrF laser with a pulse duration of 30 ns at different energy density (P) per pulse, and for comparison, the other part of the samples was subjected to rapid thermal annealing (RTA) in an uncoated argon flow at Ta = 800°C for 20 s. The distribution of bismuth in the obtained layers was studied using the method of secondary ion mass spectrometry (SIMS) by sputtering GaAs with a beam of Cs ions. For comparison with the experimental profiles, the theoretical distribution profiles of bismuth were calculated using the SRIM program, taking into account the ion sputtering of the structure surface [4]. Optical properties of the structures were studied by transmission and reflection spectroscopy in the wavelength range from 0.18 to 1.8. To study the crystal structure electron diffraction recorder was used in the "reflection" mode at a grazing angle of incidence and an accelerating voltage of 50 kV. The electrical properties were also studied by measuring the Hall effect and sheet resistance.



Optical properties

	Experimental structures						
	Sample name		Dose, 10 ¹⁴ cm ⁻²		Accelerating voltage , kV		
	Bi1-30		7				
	Bi2-30		14		30		
	Bi3-30		21				
	Bi1-80		8		80		
	Bi2-80 Bi3-80		16 24				
	Electrical properties						
	Sample	Туре	R _s , Ω/□	n(p) _s , см ⁻²		µ _H , cm²/V∙s	
	Substrate	n	2.11x10 ⁹	1.0x10 ⁶		2910	
	Bi1-30		1.67x10 ⁶	2.1x10 ¹²		1 0	
	Bi2-30	n	-		10	1.0	
			1.45x10 ⁶	3.6x	10 ¹²	1.8	
	Bi3-30		1.45x10 ⁶ 1.74x10 ⁶	3.6x 8.2x	10 ¹² 10 ¹¹	1.8 1.2 4.34	
	Bi3-30 Bi1-30-RTA		1.45x10 ⁶ 1.74x10 ⁶ 1.20x10 ⁶	3.6x 8.2x 1.0x	10^{12} 10^{11} 10^{11} 10^{11}	1.8 1.2 4.34 50	
	Bi3-30 Bi1-30-RTA Bi2-30-RTA	р	1.45x10 ⁶ 1.74x10 ⁶ 1.20x10 ⁶ 9.8x10 ⁶	3.6x 8.2x 1.0x 1.2x	10^{12} 10^{11} 10^{11} 10^{11} 10^{10}	1.8 1.2 4.34 50 54	
	Bi3-30 Bi1-30-RTA Bi2-30-RTA Bi3-30-RTA	р	1.45x10 ⁶ 1.74x10 ⁶ 1.20x10 ⁶ 9.8x10 ⁶ 1.50x10 ⁵	3.6x 8.2x 1.0x 1.2x 3.3x	10^{12} 10^{11} 10^{11} 10^{10} 10^{11}	1.8 1.2 4.34 50 54 126	
E	Bi3-30 Bi1-30-RTA Bi2-30-RTA Bi3-30-RTA Bi1-30-LA240	р	1.45x10 ⁶ 1.74x10 ⁶ 1.20x10 ⁶ 9.8x10 ⁶ 1.50x10 ⁵ 3.00x10 ⁶	3.6x 8.2x 1.0x 1.2x 3.3x 3.7x	10^{12} 10^{11} 10^{11} 10^{10} 10^{11} 10^{11}	1.8 1.2 4.34 50 54 126 5.5	
E	Bi3-30 Bi1-30-RTA Bi2-30-RTA Bi3-30-RTA Bi1-30-LA240 Bi2-30-LA240	p	1.45x10 ⁶ 1.74x10 ⁶ 1.20x10 ⁶ 9.8x10 ⁶ 1.50x10 ⁵ 3.00x10 ⁶ 1.63x10 ⁷	3.6x 8.2x 1.0x 1.2x 3.3x 3.7x 8.7x	10^{12} 10^{11} 10^{11} 10^{10} 10^{11} 10^{11} 10^{11} 10^{11}	1.8 1.2 4.34 50 54 126 5.5 5.5	



SIMS results



Calculated (1) and experimental depth distribution profiles of bismuth: (a) implantation with an accelerating voltage of 30 kV, a dose of 1.4×10^{15} cm⁻² before annealing (2) and after LA with P = 240 mJ/cm² (3); (b) implantation with an accelerating voltage of 80 kV, a dose of 1.6×10^{15} cm⁻² before annealing (2), after RTA (3), and after LA with P = 250 (4) and 400 mJ/cm² (5).

(a) Reflection spectra of GaAs (1) and GaAs samples irradiated with Bi ions with an accelerating voltage of 30 kV: after implantation (2), RTA (3), and LA (4) with P = 240 mJ/cm2. (b) Transmission spectra of GaAs (1) and Bi-irradiated samples after after TA – ion doses 8×10^{14} (2) and 2.4x10¹⁵ cm⁻² (3); after LA with P = 250 (4)



Electron diffraction results





and 400 mJ/cm² (5).

Electron diffraction patterns: implantation with an accelerating voltage 80 kV with a dose of 2.4×10^{15} cm⁻² before annealing (a), after LA with an P = 250 (b) and 400 mJ/cm² (c); implantation with an accelerating voltage of 80 kV with a dose of 1.6×10^{15} cm⁻² after RTA(d).

(b)

Conclusion

The paper shows the possibility of ion-beam doping of gallium arsenide with bismuth. The experimental profiles of the impurity distribution over the depth of the structure differ from the calculated ones; bismuth segregates to the surface, which may be due to target heating when using a pulsed ion source. The paper also shows the efficiency of using fast thermal and pulsed laser annealing to restore the crystal structure of samples, as evidenced by the reflection spectra and electron diffraction patterns. The transmission spectra indicate a decrease in the band gap in GaAs:Bi. The band gap values estimated from the spectra for GaAs with bismuth give Eg \approx 1.398 eV at room temperature, which is less than 1.42 eV for GaAs.

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