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Accurate carrier profiling of n-type GaAs junctions

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ABSTRACT

As CMOS is approaching the 22 nm node, the importance of high-mobility materials such as Ge and GaAs is rapidly increasing. For the timely development of these new technologies accurate dopant and carrier-profiling solutions for source-drain extensions with these materials are required. Identical n-type-doped (Si, Se) layers on same and opposite type medium-doped layers on S.I. GaAs substrates will be investigated, with layer thicknesses ranging from 200 down to 50 nm and doping concentration levels up to 1e20 at/cm^3. In this work, secondary ion mass spectrometry will be used for dopant profiling. For GaAs carrier profiling, conventional spreading resistance probe, as commonly used in Si-CMOS, fails. Hence, reliable alternatives need to be found for characterizing these high–low structures. Techniques to be discussed range from the more conventional approaches such as Hall or electrochemical capacitance–voltage (performed by different laboratories), over micro-Raman spectroscopy and photo-luminescence along a beveled surface, up to more advanced approaches using scanning spreading resistance microscopy.

1. Introduction

For the timely introduction of high-mobility materials in CMOS devices, accurate dopant and carrier-profiling solutions are crucial [1]. In this work we will focus on III–V materials, and more specifically GaAs. Carrier-profiling techniques routinely used for determining the sheet resistance and carrier profile in Si devices, such as conventional four-point probe (FPP) and spreading resistance probe (SRP), unfortunately fail for GaAs. On the other hand, electrochemical capacitance–voltage (ECV) is a technique, which has been widely used for III–V materials in the past [2].

In this work we have two aims. First, we want to compare the capabilities of established techniques, such as ECV, Raman spectrometry [3], photo-luminescence (PL) [3] and Hall [2], with more recently developed techniques, such as scanning spreading resistance microscopy (SSRM) [4], on the same set of MOCVD grown, highly doped, n-type-doped (Si and Se species) sub-micrometer layers, on same and opposite type, more lowly doped, underlying layers. Second, we wish to determine which of these techniques remains useful when measuring sub-100 nm structures, as will be needed for near-future high-mobility CMOS devices.

2. Structures and tools

All structures discussed in this work have been grown using metal organic chemical vapor deposition (MOCVD),

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using trimethylgallium (TMG) and tertiarybutylarsine (TBA) as precursors for the GaAs growth and diethylzinc, silane and hydrogen selenide (H_2Se) as dopant precursors. An overview of the structures discussed in this work is shown in Table 1.

As a reference for comparison the dopant profiles have been measured with secondary ion mass spectrometry (SIMS), i.e. Quadrupole Atomica 4500 measured with O_2^+ beam at 1 keV. ECV [2] has been done at two different labs, with, respectively ECVpro from nanometrics and a Bio-Rad PN 4300 electrochemical capacitance–voltage profiler at Wroclaw.

SSRM [4] was done at Imec, with a Veeco E-scope. Measurements were done under two different conditions: (i) with a −1 V sample bias in vacuum (deflection set point of 0.5 V), (ii) and with a +3 V sample bias in air (deflection set point of 1 V). Also images at intermediate biases were recorded to study the resistance versus sample bias behavior. A full diamond, boron-doped tip mounted on a soft cantilever with a spring constant of 2 N/m has been used. The corresponding force at the lowest applied deflection set point (0.5 V) was 0.26 μN. The use of a soft cantilever and low force is essential since material removal during scanning is a serious concern due to the low hardness of GaAs. With the lower force used here, still ~5 nm material is removed during scanning (cf. Fig. 1b), whereas the results reported in the literature (using a stiffer tip, 42 N/m and higher force) indicate a removal of more than 100 nm (not shown) [5]. The samples were cleaved and the back contacts were made with GaIn eutectic and silver paint.

Since the contact itself can be viewed as a Schottky barrier and as the surface states will lead to a Fermi-level pinning around mid-bandgap, a −1 V sample bias implies a forward bias on the tip–GaAs contact (for n-type), and a reverse bias for p-type GaAs. [5].

For micro-Raman a tool with a He–Ne laser (2 μm beam diameter), was used and the ratio of the intensities in the frequency position of the TO and LO phonons was measured along a high magnification bevel obtained through etching [6]. For PL a tool was used with a beam size of 10 μm. The same bevel procedure was also used for PL. The Hall measurements were performed in a home-made system using Keithley multimeters and a magnetic field of 0.2 Tesla. In order to contact the GaAs samples very small In pellets were pushed onto the corners of a $1 \times 1\,cm^2$ sample, followed by a 30 s 380 °C forming GaAs anneal for alloy formation.

3. Staircase calibration structures

In order to extract carrier profiles from SSRM measurements one first needs to calibrate the electrical characteristics of the used B-doped diamond tips. In Si technology this is typically done with the help of commercially available staircase calibration structures, which have a series of constantly doped stairs in the dopant (resisitvity) range of interest [7]. Hence, the first step to be taken in this GaAs study was to grow similar staircase calibration structures for both n- (GB180) and p-type (GB269) material (see Table 1).

Fig. 2a and b show overlays of the SIMS, ECV carrier and SSRM resistance profiles as measured in vacuum (−1 V sample bias) for the p- and n-type staircase calibration structures. Note that some discrepancies can be observed in the ECV carrier levels of the two most

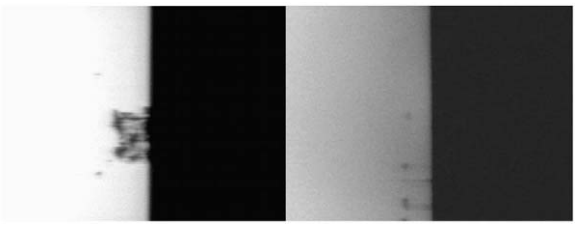

Fig. 1. Surface damage (optical microscope images) due to scanning of GaAs with two different full diamond tips: (a) 5 N/m and (b) 2 N/m.

Table 1
Overview of the GaAs structures discussed in this work.

Name	Structure	Species	Nominal concentration (cm^{-3})	Nominal thickness (nm)	Name	Structure	Species	Nominal concentration (cm^{-3})	Nominal thickness (nm)
GB180	n+	Si	5.00E+18	1500	GB181	n+	Si	5.00E+18	200
	n+	Si	1.00E+18	1500		p	Zn	~1e17	1000
	n+	Si	5.00E+17	1500		Substrate	S.I. GaAs		
	n+	Si	1.00E+17	1500					
	n	Si	5.00E+16	1500	GB183	n	As	~1e16	800
	n	Si	1.00E+16	1500		p+	Zn	~1e20	1500
	Substrate	S.I. GaAs				Substrate	S.I. GaAs		
GB269	p+	Zn	1.00E+20	1500	GB274	n+	Se	~1e19	20
	p+	Zn	1.00E+19	1500		p	Zn	~1e17	1000
	p	Zn	1.00E+18	1500		Substrate	S.I. GaAs		
	p	Zn	1.00E+17	1500					
	p	Zn	1.00E+16	1500	GB272	n+	Si	>5e18	50
	Substrate	S.I. GaAs				p	Zn	~1e17	1000
						Substrate	S.I. GaAs		
GB177	n+	Si	5.00E+18	200					
	n	As	~1e16	1000					
	Substrate	S.I. GaAs							