Technology and properties of a vector hall sensor

D. Gregušová, P. Eliáš, Z. Oszlá, R. Kúdela, J. Šoltýs, J. Fedor, V. Cambel, I. Kostić

Institute of Electrical Engineering, Slovak Academy of Sciences, Dušbravská cesta 9, 84104 Bratislava, Slovak Republic

Institute of Informatics, Slovak Academy of Sciences, Dušbravská cesta 9, 84104 Bratislava, Slovak Republic

Available online 7 July 2006

Abstract

Symmetrical four-sided ~12-μm-high pyramids with 30°-tilted sides were revealed by the etching of semi-insulating (1 0 0) GaAs substrates in 1H3PO4 × 30H2O2:8H2O at ~25 °C via sacrificial (001)-oriented Ti/GaAs/AlAs (100/2000/100 nm) etching mask patterns. The pyramids, MOCVD overgrown with InGaP/AlGaAs/GaAs heterostructure pyramids, were used as the base for magnetic field vector sensors. Each sensor consisted of three Hall probes defined on the sides of a pyramid. The device processing was realized via AZ5214-E layers deposited conformally over the pyramids by draping from water surface. While the planar reference 5 × 5-μm²-sized Hall probes exhibited a sensitivity of ~930 V A⁻¹T⁻¹ at 298 K, the sensitivity of those on the 30°-tilted facets was impossible to determine because they had a resistance of ~100 kΩ at 298 K. Further work is necessary to optimize the InGaP/AlGaAs/GaAs heterostructure growth and dopant incorporation on the 30°-tilted pyramidal facets.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Vector magnetic field sensor; GaAs; Non-planar photolithography; Hall probe; OMVPE

1. Introduction

Semiconductor device technologies on non-planar substrates allow for the realization of devices with functionalities difficult to achieve with planar technologies. For example, semiconductor magnetic field vector sensors, which are produced on planar substrates using mainstream technologies [1], can alternatively be produced on non-planar substrates [2], which can enhance their sensory properties.

We have been developing magnetic field vector sensors of unique design. Each sensor consists of three Hall probes defined on the sides of a micro-scale pyramid (Fig. 1).

The pyramids are micromachined in GaAs substrates and overgrown with a III–V semiconductor epitaxial layer (heterostructure), using metalorganic chemical vapour deposition (MOCVD).

We reported on a micro-scale GaAs-based Hall probe vector sensor defined on a symmetrical pyramid confined to facets tilted at ~20° to (1 0 0) [2]. The sensor was processed by standard photolithography with positive-tone AZ4562 resist. As AZ4562 was spin-on deposited, the layers were uneven, rendering the photolithography procedures difficult. Such non-planar resist coating is done better with spray-on rather than spin-on techniques [3,4].

As is reported in this paper, non-planar substrates can be very effectively coated with resist by the draping of resist layers from water surface. The technique was first demonstrated by Zhou et al., who coated non-planar substrates with polymethyl methacrylate to realize bismuth Hall probes, magnetic coils, and thermocouple junctions on AFM tip apexes [5,6]. We have been studying the use of the draping technique for the processing of the magnetic field vector sensors.

2. Sensor technology

The technology involves (1) three-dimensional (3D) micromachining of planar GaAs substrates to reveal pyramids confined to specific facets; (2) MOCVD overgrowth of the pyramids with a III–V semiconductor heterostructure; and (3) device processing to form the Hall probes in the overgrown facets.
2.1. Micromachining of pyramids with 30°-tilted sides

Symmetrical four-sided ~12-μm-high pyramids confined to smooth 30°-tilted sides were revealed by the etching of semi-insulating (100) GaAs substrates via a sacrificial etching mask in 1H3PO4: × H2O2:8H2O at ~25 °C (Fig. 2). The mask consisted of a top 100-nm-thick Ti layer (deposited by evaporation), and of a 2-μm-thick GaAs and a 100-nm-thick AlAs layers (grown by MOCVD). To define the mask, a pattern of convex squares defined in AZ5214-E was transferred into the Ti layer in a HF:H2O (9:1) solution at 60 °C for 5 min. Finally, the patterned substrates and a planar reference (100) GaAs substrate were cleaned in 1HF:3H2O at ~25 °C (Fig. 2). The squares had the edges in parallel with the [010], [0 10], [0 1 0], and [0 0 1] directions. The mask consisted of a top 100-nm-thick Ti layer (deposited by evaporation), and of a 2-μm-thick GaAs and a 100-nm-thick AlAs layers (grown by MOCVD). To define the mask, a pattern of convex squares defined in AZ5214-E was transferred into the Ti layer in a HF:H2O solution at ~25 °C. The squares had the edges in parallel with the [010], [0 10], [0 1 0], and [0 0 1] directions.

The GaAs/AlAs heterostructure crucially influenced the etching process via the AlAs layer that induced an enhanced and controlled lateral undercutting of the mask—a prerequisite for the revelation of pyramids instead of perpendicular stubs [7]. The micromachining was controllable both in the perpendicular and lateral directions. Conveniently, the tilt of the facets was adjustable via the ratio between the perpendicular and lateral etching rates, which was a function of the etching conditions (e.g., H2O2 content and parameters of the etching mask (e.g., the AlAs layer width) [8].

2.2. MOCVD overgrowth of the pyramids

The patterned substrates and a planar reference (100) GaAs substrate were cleaned in 1HF:3H2O at ~25 °C before being loaded into a horizontal low-pressure AIX 200 MOCVD reactor. They were overgrown with an InGaP/AlGaAs/GaAs heterostructure from arsine, phosphine, silane, trimethylgallium, trimethylaluminium, and trimethylindium.

The heterostructure consisted of a 200-nm-thick GaAs buffer layer, a 20-nm-thick Al0.3Ga0.7As spacer, a Si-doped layer, a 20-nm-thick AlGaAs layer, and a 5-nm-thick In0.49Ga0.51P cap layer. The InGaP was used for the cap layer instead of GaAs because it has a wider band gap and exhibits better chemical stability and higher resistivity. The GaAs and AlGaAs layers were grown at 700 °C, and the InGaP layer at 560 °C. The growth rates of GaAs, AlGaAs, and InGaP were 10, 12.7, and 20 nm/min, respectively, as determined from the planar (100) reference InGaP/AlGaAs/GaAs heterostructure. The rates were ~1.5 times higher on the 30°-tilted facets.

The reference heterostructure, characterized by van der Pauw measurements, exhibited a sheet resistivity ρ of 965 Ω cm, a Hall mobility μ_H of 6163 cm²V⁻¹s⁻¹, and a sheet concentration of 1.05 × 10¹² cm⁻² at room temperature. At 4.7 K, μ_H increased to 122150 cm²V⁻¹s⁻¹ and the sheet concentration decreased to 4.79 × 10¹¹ cm⁻². Planar reference Hall probes of 5 × 5-μm² and 20 × 20-μm²-sized active area were manufactured on the reference heterostructure, using standard photolithography and processing procedures.

2.3. Processing of the vector sensors

The processing included (1) definition of an AZ5214-E etching mask pattern for the transfer of the topology of the Hall probes into the pyramidal facets and the adjacent (100) surfaces; (2) transfer of the topology by Ar⁺ sputtering down through the InGaP/AlGaAs/GaAs heterostructure into the substrate; (3) definition of an AZ5214-E lift-off mask pattern for the transfer of the topology of ohmic contacts to the probes; (4) evaporation and lift-off of metallic films for the ohmic contacts; (5) Alloying of the metallic films.

The non-planar resist deposition in steps (1) and (3) was realized using the draping technique. It involved (a) the formation of a floating AZ5214-E layer on the water surface in a temperature-controlled vessel; (b) the lowering of the layer onto a patterned GaAs substrate held under the water surface in the vessel; (c) the draping of the layer over the substrate via a temperature-controlled drying process [9].

For each pattern transfer (steps (1) and (3)), a floating AZ5214-E layer was formed from a 15-μl-sized drop of AZ5214-E that spilled over the water surface in the vessel. The layer was lowered onto the substrate, dried in air during 30 min, and finally soft-baked at 90 °C for 5 min. The resultant ~5-μm-thick layer was firmly attached to the substrate. It was exposed using a standard soft-contact aligner and developed in AZ400 K at room temperature.

Fig. 3 exemplifies a mask pattern used to transfer the topology of Hall probes of 5 × 5-μm²-sized active area into the pyramidal facets of a ~12-μm-high pyramid.
The topology was transferred by etching via Ar+ sputtering in a Technics MIM/TLA-1 apparatus. Argon ions were accelerated along a $U_{acc} = 500$ V voltage drop at a current density of $J_{ion} = 0.17$ mA/cm$^2$. They were neutralized with electrons emitted from a tungsten filament. The Ar atoms hit the sample at a perpendicular angle. The sample was rotated and kept at about 25°C using Peltier elements to avoid a thermally induced damage of the AZ5214-E mask. The etching proceeded at a nominal rate of 2430 nm min$^{-1}$, determined for semi-insulating GaAs. The rate was approximately the same at the (100) surfaces and 30°-tilted facets. The root-mean-square roughness (rms) of surfaces after the sputtering process was evaluated at the top (100) surfaces of the pyramids with an atomic force microscope. It was lower than 2 nm for 5×5 μm$^2$-sized areas.

The ohmic contacts were formed from an AuGe/Ni system that was evaporated at 2×10$^{-5}$ Pa via an AZ5214-E lift-off mask onto the patterned substrates, lifted-off, and annealed at 430°C in a forming gas. Fig. 4 shows a magnetic field vector sensor after the completion of the Hall probes and ohmic contacts.

### 3. Results and discussion

A theoretical study [10] showed that the magnetic field vector sensors have their magnetic field resolution dependent on the tilt of the pyramidal facets. It was also argued the sensor based on pyramids with 45°-tilted facets should exhibit maximum field resolution.

The processing of micro-scale Hall probes on 45°-tilted facets of small pyramidal objects is a challenge mainly because it is difficult to coat such objects with resist conformally. However, conformal layers are necessary to have the exposure and development procedures reproducible.

The draping technique can coat the pyramids reproducibly with nearly conformal resist layers. When an AZ5214-E layer is formed floating on the water surface, it is relatively very planar. The planarity remains practically the same when the layer is lowered onto the substrate and firmly attached to the substrate in steps (b) and (c) [9].

In step (a), the layer is attached only loosely to a patterned substrate, but it will firmly attach to it during step (c) if the soft-bake is carried out under appropriate conditions. The layer will not adhere to the substrate in step (b) partly because it is visco-elastic and partly because water remains trapped between the layer and the substrate.

The trapped water plays a crucial role in the following soft-bake treatment: It permeates via the resist layer and moisturizes it. As a consequence, the layer becomes plasticized if the temperature is appropriate. When the AZ5214-E becomes rubbery, adhesion forces will make the layer conform to the 3D topography and adhere to the substrate. The plasticization phenomenon lies at the core of the draping technique [11].

As the sensors were processed on the pyramids with 30°-tilted facets, steps (1)–(4) were reproducibly realized with a good through-put. The InGaP/AlGaAs/GaAs heterostructure was grown under optimized conditions to achieve highly sensitive Hall sensors. Indeed, the planar 5×5 and 20×20-μm$^2$-sized probes exhibited at 298 K sensitivities of 930 and 810 VA$^{-1}$T$^{-1}$, respectively. Unfortunately, the probes on the 30°-tilted facets had a resistance of ~100 kΩ at 298 K, and it was impossible to determine their sensitivity. To achieve functional vector sensors, further work is needed to optimize the InGaP/AlGaAs/GaAs heterostructure growth and dopant incorporation on the pyramidal facets. It can be inferred that the mechanism and efficiency of dopant incorporation at the 30°-tilted facets can substantially differ from those on the (100) surfaces.

### 4. Conclusion

The technology of vector magnetic field sensors was presented. The sensors were based on an InGaP/AlGaAs/GaAs heterostructure MOCVD overgrown on symmetrical four-sided ~12-μm-high pyramids with 30°-tilted sides. Each sensor consisted of three Hall probes formed on the pyramidal sides. The pyramids were produced using a sacrificial etching technique in 1H$P_2O_7$ × H$_2$O$_2$:SH$_2$O via a Ti/GaAs/AlAs mask. The sensor processing was
realized by conventional photolithography via AZ5214-E layers nearly conformally deposited on the overgrown pyramids. The layers were deposited by draping from the water surface. While the planar reference $5 \times 5 \mu m^2$-sized Hall probes exhibited a sensitivity of $\sim 930 VA^{-1} T^{-1}$ at 298 K, the sensitivity of those on the 30°-tilted facets was impossible to determine because they had a resistance of $\sim 100 k\Omega$ at 298 K. To achieve functional vector sensors, it is necessary to further optimize the InGaP/AlGaAs/GaAs heterostructure growth and dopant incorporation on the 30°-tilted pyramidal facets.

Acknowledgements

This work was supported by the VEGA Slovak Grant Agency under projects no. 2/6096/26 and 2/6099/26 and by the CENG project.

References