Microelectronic Engineering 119 (2014) 20–23

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Sophisticated process for a spin-torque device fabricated from a pillar containing two different ferromagnetic materials separated by a non-magnetic layer

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ARTICLE INFO

Article history:
Available online 25 January 2014

Keywords:
Spin torque devices
Electron beam lithography
Poly(methyl methacrylate) (PMMA)
Cross-linked PMMA
Ion beam etching
Reactive ion etching

ABSTRACT

Since several years, devices allowing for spin manipulation in ferromagnetic layers are the subject of intensive research (e.g., Ralph and Stiles (2008) [1]). A pillar with sub-micrometer dimensions fabricated from a stack of various materials containing two or more ferromagnetic layers separated with a spacer very often serves as a core of devices suitable for investigation of spin torque phenomena. Here we describe a reliable fabrication process for such pillars emphasizing precautions which have to be taken to protect pillar side walls from surface conductivity thereby increasing the percentage of the structures revealing magnetic field/current induced switching events.

1. Introduction

In our laboratory, a molecular beam epitaxy (MBE) process has been developed which allows for the growth of high quality half-Heusler NiMnSb films on InP substrate [2]. According to [3], half-Heusler materials have a huge potential for future energy applications and for spintronics. Spin-torque devices as the one described in this paper belong to the field of spintronics. In the present study we use a stack of Ru(10 nm)/permalloy Py(6 nm)/Cu(10 nm)/NiMnSb (40 nm)/(In,Ga)As buffer (200 nm)/InP substrate (350 μm). For the experiments we need to fabricate a pillar in which current flows directly from its top (Ru layer) to the bottom ferromagnetic layer (NiMnSb) through the free ferromagnetic (Py) layer without shorting either by the side walls or by the leakage in the insulation. In addition to MBE growth, sputtering and evaporation systems we have an electron beam lithography (EBL) system (a LEO 1525 scanning electron microscope (SEM) with the attachment ELPHY PLUS from Raith GmbH). Also, a reactive ion etching (RIE) machine and a chemically assisted ion beam etching (CAIBE) system from Roth & Rau AG, and other supplementary techniques and materials in the clean room environment are available. EBL and IBE with Ar^+ ions are the most suitable techniques to define submicrometer pillars with good precision and accuracy. As described below, in addition to pillar definition in our multilevel processing we need to deposit an insulator, locally etch it with RIE, deposit some metallic contacts and connect them with big contact pads which will allow for transport measurements.

2. Device fabrication. Two possible approaches

Schematics of the desired structures are shown in Fig. 1. Ferromagnets F1 and F2 are confined in the ~250 × 500 nm elliptical pillar. Also the pillars having the cross-section axes from 100 nm for the smaller one to 2 μm for the bigger one were fabricated before we found the optimal dimensions for observation the spin torque effect. Since SEM imaging of the real samples degrade their performance, the presented SEM micrographs are from test structures imaged at various stages of process development and therefore show structures which vary greatly in size. After fabricating the isolated pillar, electrical contacts to its top and to the bottom ferromagnetic layer have to be implemented. The pillar itself can be etched either through a resist mask (using negative resist) or a metal mask (fabricated by lift-off using a positive electron beam resist). The approach with a negative resist mask is very attractive due to a smaller number of required steps and therefore a shorter total time for device fabrication.

2.1. Use of the negative resist mask for etching of the pillar

In this case the sample is coated with a reversal type resist (AR U4060 from AllResist GmbH), baked for 15 min at 90 °C and

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http://dx.doi.org/10.1016/j.mee.2014.01.013
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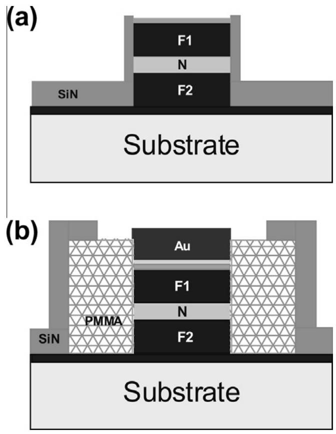

Fig. 1. Schematic image of a pillar with two ferromagnets F1 and F2 separated by a layer of normal metal N. The second ferromagnetic layer is only partly confined into the pillar; the rest of the layer is used for accessing the bottom contact. (a) A traditional arrangement of the pillar with a grown in situ Ru top layer and direct silicon nitride (insulator) coverage. (b) Our improved scheme with added top part (rest of the etching mask, Ti/Au/Ti) and protecting shield of cross-linked PMMA surrounding the pillar.

exposed in the EBL system. For 30 keV accelerating voltage the dose for exposure was varied from 400 μC/cm^2 for the big structures to 3500 μC/cm^2 for 100 × 200 nm pillars. After EBL, a post-exposure bake at 105 °C for 10 min and 25 s of UV-flood exposure are carried out, afterwards the sample is developed in a diluted sodium hydroxide containing developer (AR 300.26 from AllResist GmbH) for 2 min. The development results in a relatively high (~600 nm) resist mask (a resist pillar, Fig. 2a). After development the sample is etched with 400 eV Ar$^+$ ions at 70° ion incidence with rotation of the sample holder in the CAIBE system (IBE regime). This angle is used in order to avoid trenching around the base of the pillar, moreover additional 15 s of IBE at 10° of ion incidence are applied to clean the side walls of the etched pillars from the redeposited material. Immediately after IBE, the sample is transferred to the chamber of a PECVD (plasma enhanced chemical vapour deposition) machine (Plasmalab 80 Plus from

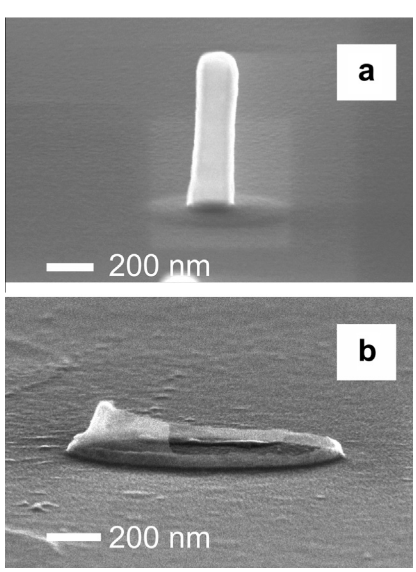

Fig. 2. (a) Negative resist column used as a mask for the pillar etching, covered with Si_xN_y after IBE. (b) Open top contact (Ru) after lift-off in NEP, the frame around is the residue of Si_xN_y.

Oxford Instruments) to deposit 40 nm of silicon nitride (Si_xN_y). Subsequently the sample is placed in a solvent (*N-Ethylpyrrolidone* (*NEP*)) at 80 °C for several hours to facilitate the following lift-off. After lift-off with assistance of ultrasonic agitation, the top Ru surface is open (Fig. 2b), which in the further steps will be connected via the leads to big contact pads.

2.2. Metal mask for etching the pillar

In the case of using a metal mask, we use a double layer of PMMA 600 K/PMMA 950 K resist for EBL. After EBL, the development in a mixture of one part of methyl isobutyl ketone (MIBK) and four parts of isopropyl alcohol (IPA) is carried out for 1 min, and the metal multilayer Ti(5 nm)/Au(100 nm)/Ti(13 nm) is deposited by e-gun evaporation in ultra-high vacuum (~10^{-8} mbar). After lift-off, we obtain metallic Ti/Au/Ti columns as a mask for the ferromagnetic pillar etching. The top Ti layer (13 nm) is removed during IBE until the bottom NiMnSb layer is bared (IBE is performed in the same way as described in Section 2.1); the uncovered Au layer serves as a top contact (Fig. 3a). At this moment the sample could be covered with an insulator (Si_xN_y), and an access to the pillar top and to the bottom layer could be provided via etching the holes in the insulator. However, as it will be described below, in order to protect the etched walls from chemicals during PECVD, an additional operation is added to the fabrication sequence before the insulator deposition.

2.3. Arrangement of the bottom contact through the insulator

The bottom contacts are made by opening areas in the insulator followed by Ti/Au evaporation. In the case of the negative mask this step takes place right after opening the top Ru contact. Thick 950 K PMMA resist (~1 μm) is deposited, and four rectangular areas (2 × 6 μm in size) are opened by EBL at a distance of few micrometers from the pillars. The Si_xN_y layer is etched through the openings in PMMA using a RIE machine with an alternation of etching with $CHF_3 + O_2$ gases and pure oxygen low power plasma cleaning. After RIE is finished, 6 s of 400 eV Ar$^+$ IBE is applied directly before the sequential evaporation of Ti(3 nm)/Au(30 nm) on the remaining resist mask. The resist thickness after the RIE is still sufficient to carry out lift-off which in this case is done in acetone. The gold rectangular outlets prepared in this way are shown on the inset a of Fig. 4. They are connected via Ti/Au leads (inset b) to big contact pads (main image of Fig. 4) in a standard EBL process with a positive resist and lift-off.

2.4. Drawbacks of the "negative resist mask" method

The structures with pillars fabricated with the negative resist mask give us quite a low yield of functioning devices (less than 1% of fabricated pillars); nevertheless a GMR (giant magnetoresistance) value of 7% for some of these devices was previously obtained at our department by Riegler [4]. However, very often the pillar resistance is either very high or too low. In the first case it can be attributed to the Ru layer detaching during the strong ultrasonic agitation. Another possible reason is a broken top contact because of standing fimbriated walls often forming along the open contact area when the lift-off process with silicon nitride is carried out. Si_xN_y, which conformally covers the resist mask laterally, is broken in an arbitrary way, so the standing frame which is visible around the contact in Fig. 2b can be even much taller than in the presented image, thereby preventing further contact of the Ru layer to the gold leads. Moreover, ultrasonic agitation provokes cracking and pin-holes in the whole film of the insulator, therefore making leakage through Si_xN_y possible (low resistance