Thermal NIL-based graphene patterning for permeable base heterojunction transistors

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High-speed data communication and RF electronics demand fast switching transistors. A new class of graphene-based transistors was proposed for this purpose [1]. Their structure leans on a classical npn silicon bipolar transistor but with the p-type base being replaced by graphene (Fig. 1). Monolayer graphene films in such graphene-base heterojunction transistors (GBHT) allow for short transit times due to the minimal base length. However, the gain of this GBHT is expected to be low due to physical transport limitations across the graphene monolayer [2]. A patterned graphene base leads to a permeable base transistor design [3] potentially allowing for much higher gain. To be able to fabricate such a permeable base GBHT (p-GBHT), a robust technology for patterning graphene has to be developed. This work aims at laterally nanopatterned graphene layers to control the transit across the base in a p-GBHT.

The developed process presents a potentially low-cost method using thermal nanoimprint lithography (T-NIL) to pattern graphene films with periodic holes. The proposed method allows for graphene patterning on an industrial scale. Our low-cost patterning approach exploits the PMMA protective layer being present on top of the CVD-grown graphene on copper substrates, eliminating the need for additional resists. This is a direct imprinting process with subsequent transfer of graphene to the functional substrate (Fig. 2a). An alternative process patterns graphene via being transferred on a substrate first and then imprinted (Fig. 2b). Substrates were either 65 nm silicon nitride (SiN) films on silicon, for process optimization, or n-doped silicon, for device fabrication.

The T-NIL process involves embossing of flexible PET molds (FleFimo, Soken Chemical and Engineering Ltd.) with pillars into mr-I PMMA 35k or 75k (micro resist technology GmbH) (Fig. 3). A sub-10 nm adhesion layer of AR-BR 5480 (Allresist GmbH) is used. PMMA spin-coating solutions were prepared by dilution in anisole (post-apply bake: 140°C, 2 mins). The embossing temperature was set at moderate 120-130°C to protect the PET mold. The relatively low temperature was compensated by a long holding time of 10-20 min [4]. Subsequently, the sub-10 nm residual PMMA layer was removed along with the adhesion layer and pattern-transferred into graphene using oxygen reactive ion etching. Subsequently, PMMA was stripped in acetone and isopropanol (Fig. 4). High-temperature annealing at 450°C in a nitrogen atmosphere for up to 5h was used to eliminate PMMA residues from the graphene if needed. The patterned graphene was inspected by optical, scanning electron and atomic force microscopy as well as Raman spectroscopy.

The p-GBHT devices were fabricated on n-doped Si wafers acting as the collector. An insulating 50 nm aluminum oxide spacer was deposited by atomic layer deposition. The CVD-grown graphene was wet-transferred on to the substrate, and the T-NIL imprint was performed. The emitter of amorphous n-doped Si (100nm) was deposited on top of the graphene by a plasma enhanced CVD process [5]. Finally, metal contacts were established, and the device was electrically characterized. A permeable base with 1.5 µm holes showed significantly reduced resistance (Fig. 5b and 6b) compared to the non-patterned graphene (Fig. 5a and 6a). However, switching could not be achieved due to the large diameter. Ongoing work with sub-200 nm holes aims at switching the base transit using a more effective Schottky barrier control.

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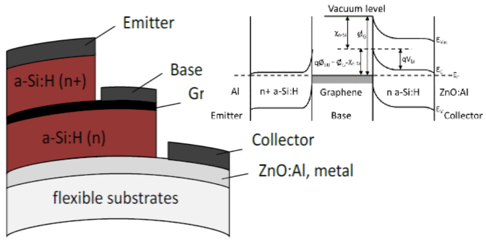

Figure 1. Device concept for a flexible GBHT device with the potential for the current modulation through a thin patterned and permeable graphene layer by controlling the Schottky barrier height.

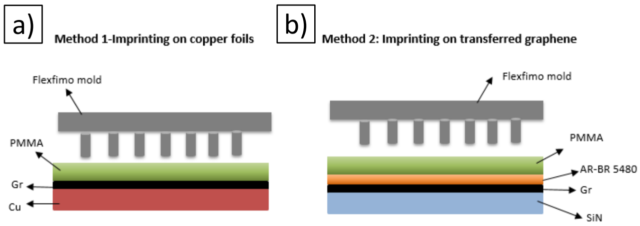

Figure 2. Methods for monolayer graphene patterning: a) direct imprinting into PMMA coated graphene (Gr) on Cu foils with subsequent wet-transfer, b) wet-transfer of Gr and subsequent imprint on an additionally coated PMMA film (preferred method due to Cu roughness).

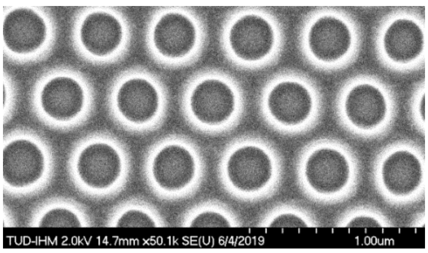

Figure 3. 200 nm hole array in 160 nm thick PMMA 35k layer after T-NIL.

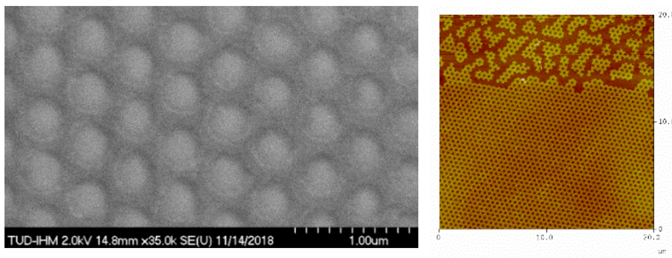

Figure 4. SEM and AFM images of holes transferred from PMMA into the graphene layer via oxygen plasma.

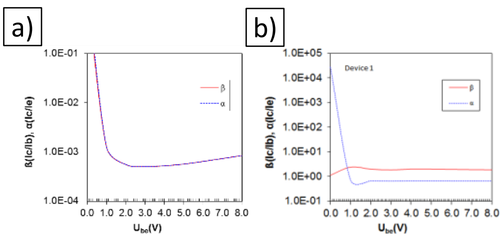

Figure 5. Gain characteristic for a) non-patterned GBHT and b) p-GBHT device after T-NIL with 1.5 µm holes.

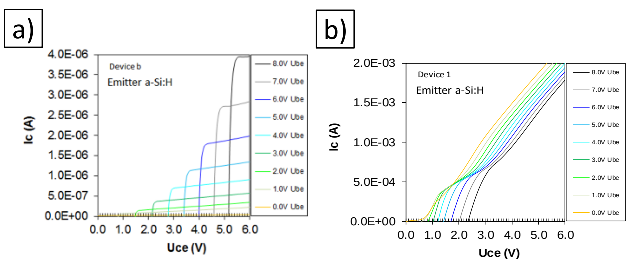

Figure 6. I-V characteristic comparison of a) non-patterned GBHT and b) p-GBHT devices after T-NIL with 1.5 µm holes.