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InP Layer Transfer with Masked Implantation

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InP layer transfer with masked implantation was investigated to eliminate ion-implantation induced damage involved in the ion-cut process. InP donor wafers were selectively implanted with hydrogen through a mask at a dose of 8.5×10^{16} ions/cm^2 at 160 keV. The layers which were subsequently mechanically exfoliated were characterized by large pyramidal protrusions on the surface, associated with the unimplanted regions. This undesirable morphology was bypassed through the inclusion of a selective etch-stop layer. The resulting structures possessed flat surfaces suitable for further bonding. This process enables the transfer of finished devices, unaffected by ion-implantation, onto a variety of desirable substrates.
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The transfer of thin indium phosphide (InP) layers onto various inexpensive substrates has been of interest in recent years.[1] A common method of layer transfer is the ion-cut (or Smart Cut) process, where hydrogen-induced layer cleavage (exfoliation) of InP is used in conjunction with wafer bonding to overcome the difficulties of epitaxial growth caused by lattice mismatch between different materials.[2] A key advantage of this process is that the donor can be repeatedly recycled following exfoliation, which is beneficial for high-cost donors such as InP.[3] Recent work with ion-cutting and adhesive bonding has shown that a prefabricated device layer transfer, i.e., the transfer of a layer with a device already fabricated on it, may be feasible in a double-flip transfer process, allowing for the integration of high-speed, InP-based devices with materials such as flexible substrates.[4] Such a process would not require any further device-fabrication processes (such as epitaxial regrowth) after transfer. However, to exfoliate an implanted InP layer using the ion-cut method, it is generally necessary to implant hydrogen ions at a high dosage of several times 10^{16}/cm^2 into the semiconductor donor.[5] Due to such high concentrations, the transferred layers suffer from implantation-induced damage, which cannot be easily remedied even through high-temperature thermal annealing beyond 600°C, at which point InP decomposes through the preferential evaporation of phosphorus.[3,6] Additional processing complications required for annealing above 600°C are the use of a capping layer or high phosphorus overpressure. It has been previously shown that limited patterned ion-cut transfer was possible in silicon, where certain regions of the transferred layers were protected from the impinging ions through a mask-based patterning.[7] In this paper, we explore a similar process in InP.

n-Type, sulfur-doped InP(100) was first coated with ~65 nm of silicon-nitride deposited by plasma-enhanced chemical vapor deposition (CVD) to protect the surface during implantation. A bilayer of Au (1.5 μm)/Ti (25 nm) metal layer was sputter deposited onto the surface and patterned into a checkerboard configuration through photolithography (see Fig. 1a). The patterns consisted of metal-patterned squares ranging from 50×50 to 1000×1000 μm. The samples were then implanted with H^+ ions at 160 keV, with a dose of 8.5×10^{16}/cm^2 at −15°C and beam current of 150 μA/cm^2. The thickness of the Au/Ti mask was calculated to be adequate to stop all incoming hydrogen in the blocked regions, according to SRIM2006 simulations.[8] Following implantation, the ion mask and silicon-nitride layer were removed through metal etchant and HF, respectively. A portion of the samples was annealed between 100 and 200°C to determine the blistering temperature, which was found to be between 125 and 150°C. Under microscope observation, it was confirmed that all blistering was confined only to the implanted regions, demonstrating the effectiveness of the Au/Ti metal layer in preventing exfoliation.

The ion-implanted, patterned InP donor was cleaned using trichloroethylene, acetone, and isopropanol and then bonded to a sapphire receptor substrate using SU-8, as shown in Fig. 1b. Sapphire was chosen as the receptor substrate to act as a temporary handle in the double-flip process due to its UV transparency and its processing resistance, which allows it to be recycled.[4] Patterned transfer can also be performed on glass, but the ensuing layer-transfer processes would have a much lower yield without a UV-transparent handle.[4] The bonded donor-receptor samples were then exposed to near-UV (350 nm) radiation designed to cross-link the SU-8 and strengthen the bond. Additional annealing at 100°C for 1 day was also carried out to further strengthen the bonding and to allow for defect nucleation and crack formation.[3] The samples were then annealed to 150°C for 1 h. A single-edge razor blade was manually inserted to mechanically cleave the InP layer from the donor (see Fig. 1c); thermal exfoliation did not occur at our chosen mask sizes but could be possible for much smaller mask features, as seen in the case of silicon.[7]

Figure 2a illustrates, through a scanning electron microscope

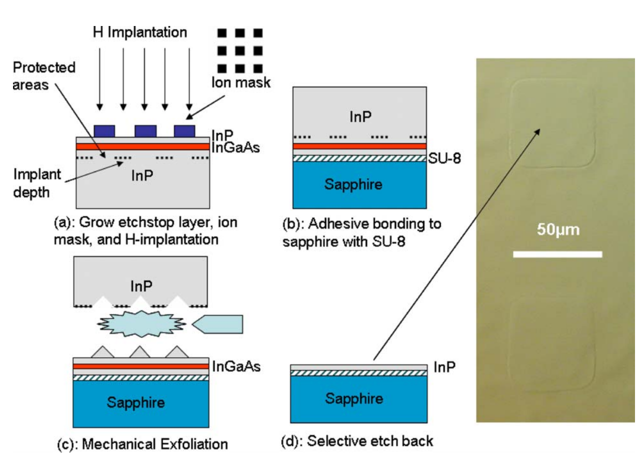

Figure 1. (Color online) Schematic of patterned transfer with selective etch back: (a) InP epilayer with etch-stop is first grown on InP, followed by ion-mask deposition and ion implantation; (b) after removal of ion mask, the donor is bonded to sapphire substrate with SU-8; (c) following heat-treatment, a blade is inserted to mechanically delaminate the layer; (d) the hillock and top layer of InP are etched away, achieving flat layer transfer. The etch-stop can also be etched off.

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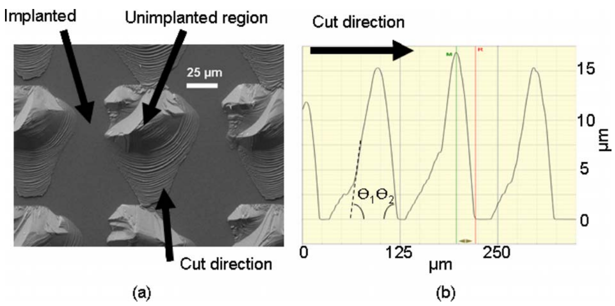

Figure 2. (Color online) (a) Top-view SEM and (b) profilometer measurement of transferred layer with 50 μm unimplanted regions.

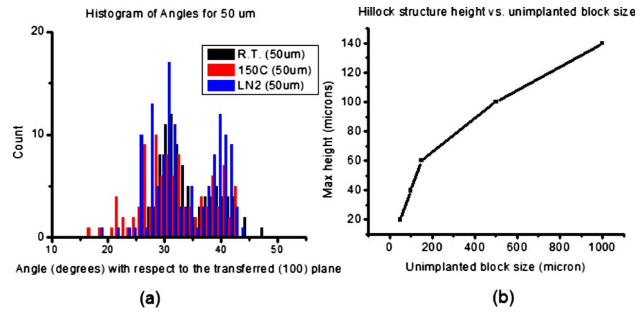

Figure 3. (Color online) (a) Histogram of angles between smooth hillock surfaces and the transferred (100) plane and (b) hillock structure height as a function of unimplanted region size.

(SEM) micrograph, the surface of the transferred InP layer (~ 1.3 μm), including 50 μm unimplanted areas in a checkerboard pattern. While the ion-implanted regions were smooth, a hillock/pyramidal morphology was observed in the unimplanted areas. Figure 2b illustrates a stylus-profilometry measurement of several such morphologies. From the observed data, we infer two distinct fracture mechanisms which occur in mechanical exfoliation: (*i*) conchoidal fracture, which appear as a series of fine clamshell lines and which is observed in the direction of blade insertion (see Fig. 2b), and (*ii*) brittle fracture, corresponding to smoother surfaces at the other end of blade insertion. The appearance of the clamshell lines has previously been observed in semiconductor materials, including InP, and is indicative of plastic deformation.[9] The surfaces corresponding to brittle fracture are steeper compared to conchoidal fracture surface and would be composed of various cleavage planes in InP. Figure 3a shows a histogram of the angles measured from the flat (100) surface to the angled pyramidal planes. The angles were estimated ($\pm 3°$) from numerous measurements. Two angular peaks were observed, one ranging between 30 and 33° and a second in the range of 39–43°. The lower peak corresponds to the conchoidal fracture surfaces (denoted in Fig. 2b as Θ_1), while the larger angle corresponded to the brittle fracture surface (denoted in Fig. 2b as Θ_2). The exfoliation was also conducted at ~ 150 and ~ -196°C (in liquid nitrogen bath), with lower and higher angles for Θ_1 and Θ_2, respectively. Such observations are consistent with an increased brittle failure with decreasing temperatures.[10]

A tentative explanation for the above observations involves the difference in the defect structure and stress, after implantation, between the two regions. Additional stress is applied during the mechanical delamination. At the onset of mechanical exfoliation, crack propagation is initiated at the edge of the implanted regions.[11] The actual crack propagation is a locally complex phenomenon. The crack front does not have to be linear but rather could propagate more rapidly through the heavily damaged implanted regions over the unimplanted islands. The crack approaching a nonimplanted region has stress concentration due to the force of the mechanical separation being localized at the unimplanted regions, because it is reasonable to assume that the crack has already moved through the local surrounding region. The crack propagation through the unimplanted region could be initiated at either of the boundaries on the region. Assuming the crack has propagated beyond the unimplanted region, there is an extremely high stress concentration at the leading and trailing edge of the island. The trailing edge would be in compression, while the leading edge would be in tension. This arrangement can result in differing fracture behavior on both edges as the crack moves from cleavage plane to cleavage plane in the unimplanted regions. Θ_2, which is close to 45°, could correspond to fracture along the (110) plane, which is the principal cleavage plane of InP.[12]

The height of the hillocklike morphologies increased with the pattern size of the unimplanted regions (see Fig. 3b). On the 1 mm patterns, a maximum height of ~ 140 μm was recorded. Such irregular and nonconformal morphology is obviously undesirable for device-layer transfer of InP. While chemical mechanical polishing can be used to remove the protrusions, we have developed an alternative method to remove such cleavage-induced artifacts. The incorporation of a selective etch back layer within the implanted region allows for the recovery of a planar surface, as schematically illustrated in Fig. 1d.[13] In this process, a 500 nm layer of InGaAs etch-stop followed by a 100 nm InP device layer was grown via metallorganic CVD. As most InP devices are fabricated on epigrown layers, the addition of an etch-stop only marginally increases the complexity of the process. As in the case with the bulk donor wafers, the unwanted protrusions were observed following transfer (Fig. 1c). However, the unwanted protrusions were removed through the use of a selective etch. The protruding InP can be etched away in hydrochloric acid solution. The samples were etched in a diluted $HCl:H_2O = 2:1$ mixture. The etch rate of the top InP layer was between 8 and 10 μm/min, while the InGaAs etch-stop was etched at a rate of 40 nm/min. An optical image of the resulting flat layer transfer is shown in Fig. 1. The InGaAs etch-stop can be selectively removed using a $H_3PO_4:H_2O_2:H_2O = 1:1:30$ solution (etch rate ~ 0.1 μm/min).

In conclusion, we have demonstrated a technique for enabling the transfer of InP device-containing layers. This method, when used in conjunction with the already demonstrated double-flip transfer process, would enable integration of high-quality InP layers onto plastic/flexible substrates as well as Si and other integration platforms. The incorporation of selective etch layers combined with patterned ion implantation leads to the full protection of the InP-based devices while recovering a planar bonding surface, leading to heterogeneous material integration without the need for post-temperature processing.

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