Electron transport properties of InAs ultrathin films obtained by epitaxial lift-off and van der Waals bonding on flexible substrates

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We investigated InAs ultrathin films on flexible substrates. InAs layers grown on GaAs(001) are separated by epitaxial lift-off (ELO), followed by van der Waals bonding (VWB) on flexible substrates. We employed "normal" and "inverted" VWB; in the former, top and bottom sides are maintained during ELO and VWB, while inverted in the latter. From the InAs on flexible substrates, we fabricated Hall-bar devices with recess etch-thinning, using which electron transport properties depending on InAs layer thickness were characterized. For the inverted VWB, we observe very high electron mobilities of InAs ultrathin films, such as $\sim$10 000 cm^2/V s for $\sim$100 nm thickness and $\sim$7000 cm^2/V s for $\sim$20 nm. These carrier mobilities are highest not only for thin films on flexible substrates but also for InAs thin films; higher than those of InAs films grown on GaAs(111)A and membranes fabricated from them. © *2010 American Institute of Physics*. [doi:10.1063/1.3459137]

Electron devices on flexible substrates, such as polyethylene terephthalate (PET) substrates, are important for lightweight, portable, and flexible electronic apparatus applications. In addition, flexible substrates with a low dielectric constant and a high resistivity can be advantageous for high-speed circuit applications, due to a low parasitic capacitance and a low leakage current. Thus, fabrication of high-speed and high-performance electron devices on flexible substrates is an interesting challenge for future electronics. However, in general, there are difficulties in deposition of high quality device active layers on flexible substrates due to strongly limited process temperatures and noncrystalline natures of flexible substrates. Although III-V semiconductors as a device active layer have excellent electronic properties, such as high electron mobilities and velocities, deposition of high-quality III-V semiconductor thin films on flexible substrates is problematic due to the difficulties. In fact, a low-temperature-deposited polycrystalline InAs film of $\sim$1 μm thickness on a flexible substrate exhibits electron mobility of $\sim$500 cm^2/V s,[1] which is far lower than that of single-crystalline InAs, while higher than that of polycrystalline Si. In order to realize high-quality III-V semiconductor thin films on flexible substrates, van der Waals bonding (VWB) of thin films, in combination with their separation from their original substrates, is promising because it does not involve the difficulties of the temperature limitation and the noncrystallinity of flexible substrates. By using the bonding method with the separation by ion-cut, a single-crystalline InP film of $\sim$1 μm thickness with electron mobility of $\sim$200 cm^2/V s was formed on a flexible substrate.[2] On the other hand, epitaxial lift-off (ELO) process[3,4] is simple and effective for the separation of III-V semiconductor thin films from their original substrates. While almost all studies about ELO and VWB on host substrates had been restricted to GaAs lattice-matched systems with a few exceptions,[5] we recently have proposed ELO-VWB process of III-V narrow-gap semiconductors obtained by lattice-mismatched growth with nanoscale thin sacrificial layers,[6] which can be applied for formation of high-quality thin films on flexible substrates. In this work, we investigated InAs on flexible substrates obtained by the ELO-VWB process. As a result, we realized InAs ultrathin films down to $\sim$20 nm thickness with very high electron mobilities on flexible substrates.

By means of molecular beam epitaxy, we grew a heterostructure for ELO-VWB shown in Fig. 1(a), InAs layer (500 nm)/AlAs sacrificial layer (4 nm)/InAs buffer layer (2500 nm)/GaAs(001). For reference, a structure shown in Fig. 1(b), InAs layer (500 nm)/GaAs(001), was also grown. The heterostructure and the reference structure, respectively, exhibit room-temperature electron mobilities of 7600 cm^2/V s and 7100 cm^2/V s, and sheet concentrations of 4.8×10^{12} cm^{-2} and 3.2×10^{12} cm^{-2}. In these structures, there are dislocation density distributions along the growth direction.[7,8] From transmission electron microscopy, we estimate dislocation density in the 500 nm InAs layer of the heterostructure, $\sim7\times10^8$ cm^{-2} near the surface and $\sim2\times10^9$ cm^{-2} at the InAs/AlAs interface. Meanwhile, the InAs layer of the reference structure possesses estimated dislocation density $\sim2\times10^9$ cm^{-2} near the surface and $\gtrsim10^{10}$ cm^{-2} at the InAs/GaAs interface. These indicate that the crystal quality of the InAs layer in the heterostructure is better than that in the reference structure.

Figure 2 shows the process of ELO and VWB on a flexible substrate. The flexible substrate is a PET substrate

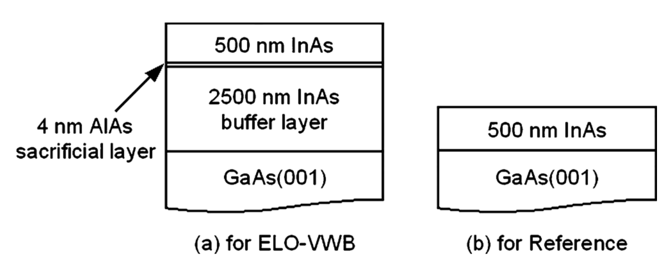

FIG. 1. (a) Heterostructure for ELO-VWB. (b) Reference structure.

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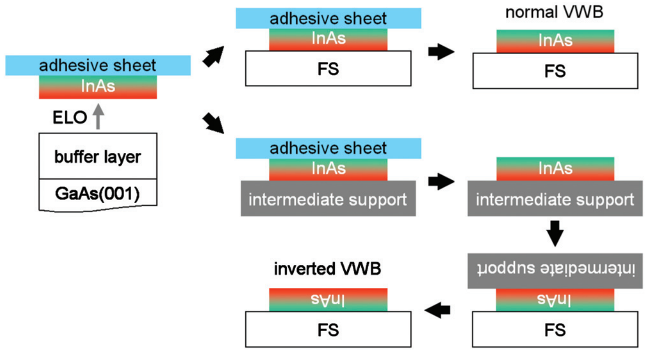

FIG. 2. (Color) The process of ELO and VWB on a flexible substrate (FS). Top and bottom sides are maintained in the normal VWB, while inverted in the inverted VWB.

(340 μm) coated by bisazide-rubber OMR85 (~500 nm). Using ~2×2 mm^2 size samples of the heterostructure, we carried out ELO, separation of the 500 nm InAs layer attached to an adhesive sheet (35 μm), acrylic-coated polymer sheet Adwill D-201, by HF selective wet-etching of the sacrificial layer. After the ELO, we realized two types of VWB shown in Fig. 2; one is "normal" VWB, in which top and bottom sides are maintained during ELO and VWB, and the other is "inverted" VWB, resulting in the top-bottom inversion. In the normal VWB process, the separated InAs layer is bonded on a flexible substrate, followed by adhesive sheet removal. On the other hand, in the inverted VWB, the separated InAs layer is first bonded on an intermediate support, a resist-coated sapphire substrate. After removal of the adhesive sheet, the InAs layer is transferred onto a flexible substrate by VWB, and then the intermediate support is removed by resist dissolution. If ELO process could be carried out after VWB of the heterostructure on a flexible substrate in the beginning, this leads to inverted VWB on the flexible substrate. However, this was impossible because a suppleness of the adhesive sheet is necessary for progression of the selective wet-etching of the nanoscale thin sacrificial layer, whose thinness is to keep the crystal quality of the InAs layer. In order to realize firm VWB via deionized water, we employed oxide removal from the InAs surface and hydrophilic treatments using oxygen plasma of the flexible substrate surface. As a result, we obtained normal and inverted VWB InAs layers on flexible substrates, both of which are available for subsequent device fabrication process.

Owing to the dislocation density distribution along the growth direction in the InAs layer, the normal VWB InAs layer has lower dislocation density in the top side, while the inverted VWB InAs layer has lower dislocation density in the bottom. Therefore, we expect a different crystal quality between normal and inverted VWB after etch-thinning. This can be studied by characterization of electron transport properties depending on the layer thickness using InAs Hall-bar devices with recess etch-thinning. We fabricated the Hall-bar devices from the normal VWB InAs on flexible substrate, the inverted VWB InAs on flexible substrate, and also the reference InAs on GaAs(001), as follows. First, device mesas were isolated by wet etching. Figure 3(a) shows an optical microscope image of a device mesa on a flexible substrate. There was no penetration of wet etchant into the InAs/flexible substrate interface due to the firm bonding, as confirmed by observation from the backside of the flexible

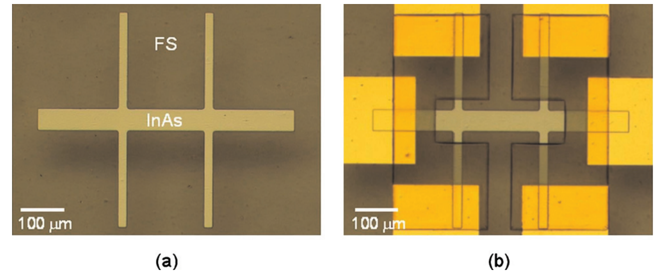

FIG. 3. (Color) Optical microscope images of (a) an isolated InAs Hall-bar device mesa on a flexible substrate (FS) and (b) a Hall-bar device on a FS with the resist patterning of the active region for recess etch-thinning.

substrate. Next, nonalloy Ohmic Ti/Au electrodes are formed by conventional metal evaporation and lift-off. Furthermore, we carried out resist patterning of the device active regions for recess etch-thinning. As shown in Fig. 3(b), we obtained Hall-bar devices on flexible substrates with the resist patterning, using which we repeated recess etch-thinning by $H_3PO_4-H_2O_2-H_2O$ wet-etchant and measurements. The InAs layer thickness was determined by scanning confocal laser microscope measurements, with cross-checking by a step profiler. Electron transport properties were characterized by Hall measurements at room temperature.

Figure 4 shows electron mobilities and sheet concentrations as functions of InAs thickness obtained by measurements of many devices. Both the normal and inverted VWB InAs give higher electron mobilities than that for the reference, indicating that our ELO-VWB method is effective to realize high-quality InAs ultrathin films on flexible substrates. Moreover, in comparison with the normal VWB, the

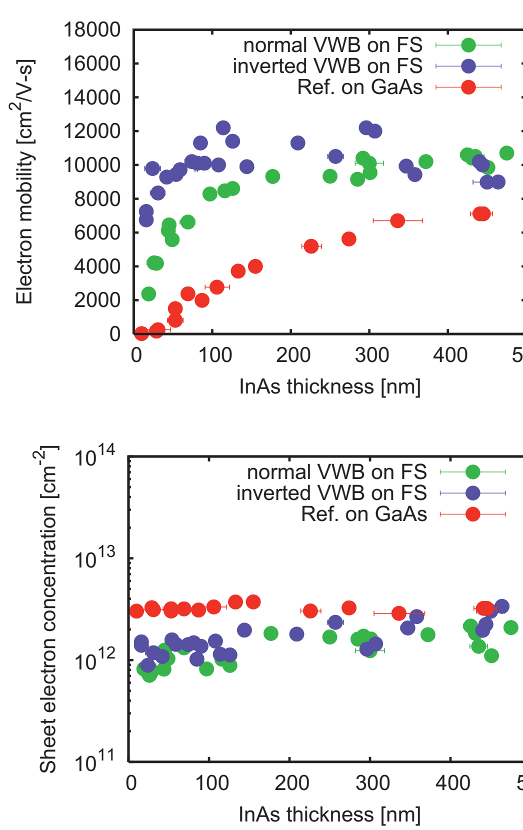

FIG. 4. (Color) Room-temperature electron mobilities (above) and sheet concentrations (below) for normal VWB on flexible substrate (FS), inverted VWB on FS, and reference on GaAs(001), as functions of InAs thickness.

inverted VWB InAs after thinning exhibits high electron mobilities as expected, such as $\sim$10 000 $cm^2/V\,s$ for $\sim$100 nm thickness and $\sim$7000 $cm^2/V\,s$ for $\sim$20 nm. While the normal VWB and the reference give electron mobilities monotonically decreasing with decrease in the thickness, being consistent with the dislocation density distributions, the inverted VWB InAs does not. For the inverted VWB InAs, with decrease in the thickness, the electron mobility once slightly increases for the thickness down to $\sim$100 nm, which is consistent with the dislocation density distribution but followed by a decrease for the thickness $\lesssim$100 nm. Due to the Fermi energy pinning of InAs,[9,10] there are conduction electrons accumulated at the surfaces and the interfaces (InAs/flexible substrate or InAs/GaAs) in spite of the undoped InAs growth. The observed sheet electron concentrations are dominated by the electrons at the surfaces and the interfaces, and thus do not exhibit pronounced thickness dependence. The reference exhibits higher sheet electron concentrations than the normal and inverted VWB, owing to the interface electrons caused by high-density dislocations at the InAs/GaAs interface. The decrease in the electron mobilities for the inverted VWB InAs of the thickness $\lesssim$100 nm can be attributed to scattering of the surface electrons by the interface random potential, and also scattering of the interface electrons by the surface random potential, which should affect the electron mobilities also for the normal VWB and the reference.

For the inverted VWB InAs, we obtain highest carrier mobilities not only for thin films on flexible substrates but also for InAs thin films. Previous studies show that InAs grown on GaAs(001) exhibits electron mobilities similar to those of our reference, such as $\sim$5000–8000 $cm^2/V\,s$ for $\sim$500 nm thickness, $\sim$2000 $cm^2/V\,s$ for $\sim$100 nm,[11,12] indicating difficulties of realization of high-quality InAs ultrathin films due to the high-density dislocations at the InAs/GaAs(001) interface. On the other hand, growth of InAs on GaAs(111)A provides lower defect densities at the InAs/GaAs interface, and thus better thin films, whose electron mobilities are $\sim$3000–4000 $cm^2/V\,s$ for 50–100 nm thickness. Moreover, free-standing InAs membranes fabricated from the InAs films on GaAs(111)A exhibit high electron mobilities such as $\sim$7500 $cm^2/V\,s$ for 50–100 nm thickness.[13] Our inverted VWB InAs ultrathin films exhibit even higher electron mobilities. This can be applied to InAs field effect transistors (FETs),[14] in particular thin-film FETs on flexible substrates, a kind of thin body III-V semiconductor-on-insulator FETs.[15] In addition, we can expect an extension to applications to InAs tunnel FETs.[16–18]

In summary, we investigated InAs ultrathin films on flexible substrates obtained by ELO-VWB. We obtained very high electron mobilities of InAs ultrathin films on flexible substrates. This can open up InAs thin-film device applications on flexible substrates.

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