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Nitrogen-mediated aligned growth of hexagonal BN films for reliable high-performance InSe transistors

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Orientation controlled hexagonal boron nitride (h-BN) films exhibits excellent mechanical and thermal properties, making them attractive for diverse applications. However, wafer-scale synthesis of vertically oriented h-BN films is still a significant challenge. Herein, utilizing high power impulse magnetron sputtering (HIPIMS) of up to around 500 W, a series of h-BN thin films have been directly deposited on silicon wafers at various nitrogen environment. Our analyses reveal that the degree of microstructure alignment of the as-grown films strongly depends on the nitrogen gas flow ratio. Between 20% to 40% gas flow ratio, defined to be the ratio of nitrogen gas flow rate to the total gas flow rate of nitrogen and argon, the films attained its maximum alignment as measured by the R value. Correspondingly, the maximum thermal conductivity of the films occurs in the same region and the value ranges from 0.5 to 1.5 Wm⁻¹K⁻¹. Interestingly, such BN-encapsulated InSe transistor shows a typical semiconductor characteristic and works well even after 2 months or longer. Additionally, InSe transistor exhibits electro-dominated transport with high mobility (71.0 cm²V⁻¹s⁻¹) and performs well up to 200 °C. Our study suggests that the alignment engineering in h-BN samples is plausible for thermal performance enhancement, which can broaden the thermal management applications in electrical and optoelectronic field.

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Introduction

As a wide band gap material of ~ 6 eV, hexagonal boron nitride (h-BN) offers great promises in many areas of research and industrial applications because of its excellent mechanical, optical and thermal properties.^{1–3} Orientation engineering of layered materials has been widely applied to other two-dimensional materials, such as graphene and molybdenum disulphide (MoS₂), for energy conversion and storage applications.^{4–6} In the case of h-BN, vertically aligned h-BN occurs when the hexagonal basal plane of h-BN is aligned perpendicularly to the substrate surface. Its first hints of existence comes as an intermediate phase between the cubic boron nitride (c-BN) and the substrate alongside turbostratic (t-BN) and amorphous boron nitride (a-BN) in the depositions of c-BN.^{7–10} Subsequently, h-BN nanowalls (h-BNNWs), which have layers of h-BN vertically aligned to the substrate surface with voids between each “walls”, have been reported.^{11,12} One of current methods for depositing vertically aligned h-BN films is plasma-enhanced chemical vapour deposition (PECVD). Another approach is magnetron sputtering which is a suitable

method for depositing thin films for industrial applications. Despite that, low deposition rate during the sputtering process and low quality of the thin films severely limit its industrial applicability. As a pulsed magnetron sputtering, high power impulse magnetron sputtering (HIPIMS) is known for its high target power densities and high ion densities during the process, resulting in better film adhesion, higher hardness, improved surface roughness and denser films.^{13–15} Besides, HIPIMS can directly deposit h-BN on Si wafer and enables the integration with the industrial semiconductor processes.^{16,17} In this work, h-BN samples under various reactive nitrogen atmospheres have been directly deposited on Si wafer using HIPIMS and a pure boron target. It is found that the thermal conductivity is directly related to the alignment of the h-BN films which can manipulated via control of the nitrogen gas flow ratio. Moreover, the maximum value of thermal conductivity in the aligned film is around 300% higher as compared to its amorphous counterpart. While InSe transistor exhibits an insulating behaviour without BN layer due to its exposure to environments (moisture and air), the BN-encapsulated device remains as a semiconductor with high electron mobility. Furthermore, such devices can work well after two months and even at high temperature of up to 200 °C. Our study gave insights into the orientation engineering on h-BN thin films for electronic devices, with potential photonics and energy storage applications.

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†Electronic Supplementary Information (ESI) available: Deposition parameters, XPS table of peak positions differences and EDS spectra of h-BN and InSe film. See DOI: 10.1039/x0xx00000x

Experimental section

Preparation of h-BN thin films

The boron nitride films were deposited using HIPIMS system. The target is 3-inch diameter pure boron target (99.99%) with copper plate as backing using InSn alloy as an adhesive. 350- μm double-sided polished <100> silicon wafers were diced and used as the substrates. Prior to each deposition, the substrates were first cleaned with acetone, then isopropanol and rinsed with deionized water. They were then blown dry with nitrogen. During the process, the chamber is first pumped down to $\sim 4 \times 10^{-6}$ Torr. Depositions were carried out in a reactive atmosphere with mixed Ar and N_2 gases (total 100 sccm) which are introduced into the chamber. The gas flow ratio is defined as the ratio of the gas flow rate of nitrogen to the combined gas flow rates of argon and nitrogen. Meanwhile, the temperature of the substrate holder is set at 800 $^\circ\text{C}$ and the average power supplied to the target ranges from 200 W to 280 W. Variance in the values is due to the efforts in stabilizing the boron plasma. A total of 6 samples, labelled A-F, were deposited and detailed deposition conditions are tabulated in Supporting Information, Table S1. Each deposition was conducted for 180 minutes.

Preparation of InSe transistors

Pure InSe was synthesized by microwave assisted chemical vapor deposition (MACVD) method. Experimental details on its synthesis can be found in previous work.¹⁸ Indium beads and selenium powder, purchased from Sigma-Aldrich without further purification, were mixed and placed in one-end quartz tube. A neck was deliberately made before the mixture were pumped into high vacuum ($\sim 10^{-7}$ torr). The neck was sealed and placed into a custom-designed microwave plasma system for solid state synthesis. The sealed ampoule was surrounded by argon plasma sustained through continuous microwave irradiation. The argon pressure was kept at 37 Torr. Microwave power was around 750 W and adjusted to maintain the temperature of source mixture at 630 $^\circ\text{C}$. BN-encapsulated InSe transistor was fabricated by lithography, electron-beam deposition and lift-off process.

Characterization

The h-BN films deposited were characterized using Raman Spectrometry, Fourier-Transform Infrared Spectrometry (FTIR), Scanning Electron Microscopy (SEM) and Transmission Electron Microscope (TEM), FEI Tecnai™ G2 F20. The thickness of the films was measured using Bruker DektakXT surface profiler with the Vision64 software. Elemental composition was measured using Electron Energy Loss Spectrometry (EELS) and Energy Dispersive Spectrometry (EDS). X-ray Photoelectron Spectrometry (XPS) was conducted to investigate the bonding characteristics of the film. PHI Quantera II from ULVAC-PHI was used for this XPS study, it uses Al K α X-ray source with energy of 1486.6 eV, and argon as the ion sputter gun. Thermal conductivity of each film is measured using the NanoTR technique.¹⁹ NanoTR is based on the phenomenon of how

temperature changes the reflectivity of light, termed as thermo-reflectance.

Results and discussion

FIG. 1(a) shows a schematic of the HIPIMS setup. The pure boron target is sputtered in an environment with nitrogen and argon as gases. Argon functions as the active gas, it sputters off the boron species from the boron target. Meanwhile, nitrogen gets dissociated due to the high electron density within the plasma and reacts with the boron species, thereby forming boron nitride films on the silicon substrate. FIG. 1(b) reveals how the current and the voltage varies with time for a typical HIPIMS pulse. Typically, a voltage pulse lasts up to 30 μs and can reach up to 1 kV. The peak current can reach up to hundreds of amperes, generating a high power (~ 500 W) in a short time. This gives a high average power to the boron target during depositions, which resulted in the power densities to be around 26 W cm^{-2} , higher than that of direct current (DC) magnetron sputtering at similar average power supplied to the target.

FIG. 1 (a) A schematic of the HIPIMS setup. (b) Voltage and current pulses of a typical HIPIMS system.

FIG. 2(a) – (c) demonstrate the SEM images for the samples corresponding to gas flow ratios of (a) 5%, (b) 20% and (c) 85%. Apparently, the domain size of h-BN films decreases as the nitrogen gas flow ratio increases. FIG. 2(d) – 2(e) show cross-sectional HRTEM images of the h-BN film on the Si substrate and of the interface between the h-BN film and the silicon substrate. There is a 14 nm thick of amorphous boron nitride at the interface. The layer may provide a template on which aligned h-BN may grow on it. The elemental composition of the film was investigated by EDS and EELS. FIG. 2(f) is an EELS spectrum of a sample deposited by pure boron target, used to ascertain the presence of sp^2 bonding within the film. It is observed that the boron-K edge, carbon-K edge and nitrogen-K edge are present, which agree well with the previous results for h-BN.²⁰ The sharp π^* peak at the onset of the boron-K edge indicates the excitation of K-shell electrons into the antibonding π^* states,²¹ correspondingly indicates the sp^2 -bonded character of the h-BN film.²² The broader σ^* unoccupied peak is due to excitations of the K-shell electrons into the antibonding σ^* states.²¹ EDS analysis further reveals the presence of boron and nitrogen. FIG. 2(g) – 2(i) show the elemental distributions of Si, B, and N within the sample, (g) Silicon, (h) Boron and (i) Nitrogen.

FIG. 2 SEM images of samples corresponding to (a) 5%, (b) 20% and (c) 85% gas flow ratios, the scale bar denotes 0.5 μm. (d) Cross-section TEM image of the sample corresponding to 20% gas flow ratio, the scale bar denotes 500 nm. (e) HRTEM image of the interface between the h-BN thin film and the silicon substrate. A 14nm thick amorphous BN layer exist between the interface, the scale bar denotes 5 nm. (f) EELS spectrum of a sample deposited using pure boron target. EDS map scan of (g) silicon, (h) boron and (i) nitrogen for the sample corresponding to 20% gas flow ratio.

Moreover, owing to the utilization of pure boron target, boron is more sparsely distributed as compared to nitrogen which is more uniformly distributed.

FIG. 3(a) depicts the Raman spectra for the samples A - F. All samples except Sample A shows a single peak which is assigned to the Raman-active E_{2g} phonon mode, the in-plane anti-symmetric vibration between the B and N atoms within the hexagonal ring.²³ The peak becomes more pronounced as the gas flow ratio of the samples increases, indicating the stronger presence of E_{2g} mode at higher gas flow ratios. The highest intensity for the E_{2g} mode occurs for Sample F, which corresponds to the gas flow ratio of 60%, indicating that the highest proportion of h-BN occurs in Sample F. The wavenumber corresponding to the E_{2g} mode is around 1370 cm^{-1} , which is slightly blue-shifted from the characteristic 1367 cm^{-1} corresponding to the E_{2g} mode in bulk h-BN.²⁴ The blue-shifting of the peak may be indicative of the high compressive stress and is similar to the peaks observed in h-BN deposited using atomic layer deposition,²⁵ chemical vapour deposition²⁶ and by

chemical methods.²⁷ FIG. 3(b) shows the FTIR spectra for samples A - F. In these spectra, both the A_{2u} and E_{1u} infrared-active phonon modes are present. The presence of these two characteristic modes are indicative of the presence of h-BN. It should be noted that the A_{2u} mode gets blue-shifted to higher wavenumbers as the gas flow ratios of the samples increases. The peak that is assigned to the E_{1u} mode is around 1370 cm^{-1} to 1380 cm^{-1} , which is expected of h-BN. As expounded above, it can be ascertained that these samples contain predominantly h-BN. XPS analysis further confirm the presence of hexagonal B-N bonding (FIG. 3(c) – (e)). It can be seen from FIG. 3(c) that the as-grown films contain both B and N. Moreover, the peak positions of B 1s and N 1s are around 396.2 eV and 189.1 eV, which is consistent with the previous values of hexagonal BN.²⁸ Notably, the difference XPS peak positions of both B and almost remains constant, regardless of the variation of nitrogen gas flow ratio, at around 207 eV (Table S2), signifying the presence of h-BN.

FIG. 3 (a) Raman spectra for the samples. (b) FTIR spectra for the samples. (c) XPS spectra of the samples. (d) High resolution XPS B 1s spectra of the samples. (e) High resolution XPS N 1s spectra of the samples. (f) Comparison of the peaks of the binding energies of both B 1s and N 1s between different samples.

FIG. 4 (a) Wavenumber of the peak corresponding to the h-BN A_{2u} and E_{1u} modes variation with the samples' gas flow ratio. (b) R Value variation with the samples' gas flow ratio. The curve fit is done using a compressive-stress model. HRTEM images of (c) random and (d) vertically aligned h-BN films, corresponding to 5% and 20% gas ratio. The insets in (c) and (d) are the corresponding SAED patterns, further confirming the random and oriented arrangements of h-BN.

To investigate the orientation of the h-BN film grown, the R Value is a method of approximating the proportion of aligned h-BN within the sample. The R Value, calculated from a sample's FTIR spectrum, is defined to be the ratio of the intensity corresponding to A_{2u} peak to the intensity corresponding to the E_{1u} peak.^{29–31} The equation is illustrated below:

$$R = \frac{I_{A_{2u}}}{I_{E_{1u}}} \quad (1)$$

The origin of the alignment of h-BN in such thin films is typically attributed to the high compressive stress experienced by the h-BN film.^{8,10,29} A compressive stress model has been frequently used to account for the stress variation in thin films:^{32,33}

$$\sigma \propto \frac{\sqrt{E}}{\frac{R}{J} + kE^{\frac{5}{3}}} \quad (2)$$

where $k = 0.016\rho E_0^{-5/3}$, J is the ion flux, E is the ion energy, and ρ , E_0 and R are material related parameters. This equation has been used in the fitting of FIG. 4(b) and FIG. 5(c) to illustrate the relationship between the alignment of the h-BN film and the compressive stress exerted on the film. The peak of the R value is close to where the peak of the fitting of the compressive stress model and the peak of the thermal conductivity values.

This result highlights the strong correlation between the high compressive stress experienced by the film which in turn results in an orientated film and consequently improves the thermal conductivity.

FIG. 4(a) shows the variation of the peak locations of both the E_{1u} and A_{2u} optical phonon modes due to a change in the size of the h-BN crystallite. As shown in FIG. 4(b), R value is calculated for each sample and is plotted based on the Equation 2. In general, the alignment is closely related with the compressive stress experienced by the films. In addition, HRTEM was used to view the samples corresponding to 5% and 20% gas flow ratio as they have the lowest and highest R values amongst the samples, respectively. The high magnification images are shown in FIG. 4(c) – 4(d). It is clear that the h-BN is randomly orientated in 5% nitrogen gas flow ratio, whereas it is highly aligned in 20% nitrogen gas flow ratio. Meanwhile, the interplanar distances are 0.349 and 0.344 nm, which is close to the theoretical 0.333 nm in bulk h-BN.³⁴ Furthermore, the diffraction arcs and d-spacings shown are assigned to (002), (111) and (010) planes of h-BN.

To investigate how the orientation of the films will affect the thermal properties, the thermal conductivities of the samples were measured using the Thermo-reflectance method, using the NanoTR equipment. A 100 nm layer of Aluminium was deposited prior to the measurement as a transducer. FIG. 5(a)

FIG. 5 (a) A schematic diagram showing the Thermo-reflectance method to measure thermal conductivities of the samples. (b) The plot of both the raw and fitting signals of the sample corresponding to 20% gas flow ratio. (c) The variation of thermal conductivities, the points are fitted with a compressive stress model. (d) Temperature-dependent thermal conductivity of h-BN film grown at 5% and 20% nitrogen gas flow ratios.

FIG. 6 (a) A schematic showing how the varying the nitrogen gas flow ratio in the deposition will result in different microstructures of the deposited film. (b) A HRTEM image showing the h-BN film is deposited onto the silicon substrate without a transition layer. The panels show the magnified images at two locations, the panel at the top right shows the random orientation of h-BN. (c) A HRTEM image showing the transition layer consisting of amorphous boron nitride (a-BN) between the silicon substrate and the h-BN film. The panels show the magnified images at two locations, the panel at the top right shows the aligned orientation of h-BN.

gives the schematic of the working principle of the thermo-reflectance method. The raw signal from the equipment and corresponding fitting are shown as in FIG. 5(b). The thermal conductivities of the samples measured were plotted on FIG. 5(c). The fitting function used in FIG. 5(c) is the dependency of the film compressive stress on the ion energy (Equation 2). The highest thermal conductivity is at $1.5 \text{ W m}^{-1} \text{ K}^{-1}$ and corresponds to the sample deposited at 20% nitrogen gas flow ratio. This value is 300% higher than the lowest thermal conductivity measured at around $0.5 \text{ W m}^{-1} \text{ K}^{-1}$ which occurs to the sample deposited at 5% nitrogen gas flow ratio. A slight increment in the gas flow ratio of nitrogen can induce an increase in the sample's thermal conductivity. The thermal conductivity peaks within a range of 20% to 40% nitrogen gas flow ratio. FIG. 4(c) highlights that the orientation of the film as shown in FIG. 5(b) as a strong correlation to the thermal conductivity of the film. The highly orientated the film is, with the h-BN c-axis orientated parallel to the substrate surface, the higher the thermal conductivity of the film. As the film is aligned, the phonons are less likely to be scattered. This gives rises to a simple method of controlling the orientation of the h-BN film and hence, its thermal conductivity, via the simple calibration of the nitrogen gas flow ratio during depositions. FIG. 5(d) shows the

temperature variation of thermal conductivities corresponding to two samples. The samples correspond to 5% N₂ gas flow ratio and 20% N₂ gas flow ratio. It is shown that the thermal conductivity drops sharply as temperature increases from room temperature (approximately 25 °C) and it stabilizes above 100 °C to 300 °C. This stability gives strong confidence that the film can perform its heat dissipation function even at high temperatures. The thermal conductivity at 300 °C of the sample corresponds to 20% N₂ gas flow ratio falls around 42% from its maximum value recorded at room temperature, similar to the decrease that occurs to 5% N₂ gas flow ratio which is around 40%.

The growth mechanism of vertically aligned h-BN is proposed. As pure boron target is a dielectric target, it has low secondary electron yield. Consequently, the dissociation of nitrogen molecules into nitrogen species (atoms or ions) occurs to a lesser degree. At low nitrogen gas flow ratio, the deposition is starved of nitrogen species to interact with the sputtered boron species to form h-BN. This leads to poor stoichiometry between the nitrogen and boron species, leading to insufficient bond formation. The absence of a transition layer which serves as a template for the growth of aligned h-BN may account the poor degree of alignment for the h-BN films deposited. This leads to

poor thermal conductivity of the sample corresponds to the low nitrogen gas flow ratio, as evident from FIG. 4(b) and FIG. 5(c). Evidently, FIG. 6(b) highlights the absence of the transition layer in between the silicon substrate and the h-BN layer deposited. The top right panel of FIG. 6(b) shows the polycrystalline nature of the h-BN film deposited. The clusters of h-BN are demarcated by the white dotted borders. Enhancement of alignment and hence, thermal conductivity is achieved at higher gas flow ratio, within a range of gas ratios. The ion bombardment of nitrogen and boron ions is critical in creating the compressive stress environment that enables the formation of aligned h-BN. Existence of transition layer may provide a template for the aligned growth of h-BN. FIG. 6(c) depicts the h-BN film grown on a silicon substrate on a transition layer consisting of a-BN. The transition layer is demarcated with white dotted lines. The

alignment of the h-BN film is shown on the top right panel of FIG. 6(c). As the gas flow ratio of nitrogen gas is further increased, bombardment of ions onto the substrate is hindered by the presence of neutral nitrogen gas that impedes the direct line-of-sight path from the target to the substrate.

High-quality InSe crystal was synthesized by microwave-assisted CVD method. Detailed experimental procedures can be found in our previous work.¹⁸ FIG. 7(a) and 7(b) exhibit the atomic structure of InSe held together by covalent bonds, indicating the similar hexagonal structure to h-BN. Three typical Raman peaks at 115.7, 177.8 and 227.8 cm^{-1} are present (FIG. 7(c)), which is corresponded to the A_{1g}^1 , E_{2g}^1 , and A_{1g}^2 phonon modes.³⁵ On the other hand, TEM is used to characterized the crystal structure of InSe films. FIG. 7(d) – 7(f) show the element mapping of In and Se. Quantitative analysis indicates the ratio

FIG. 7 (a) Side view and (b) top view of the InSe crystal. (c) Raman spectrum of the as-grown InSe sheet. EDS mapping images, (d) electron image, (e) mapping of Se, (f) mapping of In. (g) HRTEM image of InSe showing different layers stacked. (h) High magnification HRTEM image and (i) corresponding SAED patterns of microwave-assisted synthesized InSe sheet.

of In and Se is around 1:1 (FIG. S2), which agrees well with the beta InSe.³⁶ FIG. 7(g) – 7(h) reveals the high quality of the as-grown InSe crystals. The lattice constant, denoted as 'd' in FIG. 7(b), is about 0.391 nm, while the angle between (100) and (010) planes is around 120°, which is consistent with the reported hexagonal structure of ϵ -InSe.³⁷ Meanwhile, the corresponding SAED pattern along the incident zone axis $\langle 001 \rangle$ is shown in FIG. 7(d). Notably, the presence of a typical six-fold symmetry also indicates the excellent crystalline quality of hexagonal InSe thin films.

FIG. 8(a) demonstrates a schematic illustration of our BN-encapsulated InSe field effect transistor (FET) device with electrical connections. Under the bias voltage of 5 V, InSe transistor with BN film exhibits a typical semiconducting behaviour, whereas it becomes insulative without BN encapsulation (FIG. 8(b)). Apparently, h-BN film can be viewed a protective or passivation layer and improves the performance of the InSe device which is very sensitive to environment, such as moisture and air contamination. Consequently, most InSe-based transistors are fabricated in gas-protected drybox.³⁸ Owing to the h-BN encapsulation effect, our InSe transistor reveals a good semiconducting I-V curve, even after 2 months

(FIG. 8(c)). When applying a gate bias from -70 V to 70 V, the transport characteristics of our device are shown in FIG. 8(d). The I_{ds} increases as the bias increases. The mobility of InSe transistor can be extracted from the following equation:³⁹

$$\mu = \frac{L}{(WC_{ox}V_{ds})} \times \frac{dI_{ds}}{dV_g} \quad (3)$$

where L is the channel length, W is the channel width, C_{ox} is the gate capacitance ($1.21 \times 10^{-4} \text{ F m}^{-2}$), V_{ds} is the bias voltage, I_{ds} is the current, and V_g is the gate voltage. According to the inset of FIG. 8(d), the mobility of InSe transistor is calculated to be $6.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ under room temperature. This value of our InSe device is superior to those of MoTe_2 ($0.2\text{--}2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and also comparable to PtSe_2 transistors ($7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$).^{40,41}

Measurements done on InSe transistor is first carried out at room temperature, and temperature is increased to 200°C incrementally. FIG. 9(a) and 9(b) demonstrate the transport characteristics and the corresponding mobility of InSe FET, indicating a remarkable n-type semiconducting carrier transport. According to the transfer curves, the mobility of this device increases from 11.3 to $71.0 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ as the temperature varies from 100°C to 200°C . FIG. 9(c) shows the band structure

FIG. 8 (a) Schematic illustration of the BN-encapsulated InSe transistor. (b) I-V curves of InSe transistor with and without BN protective layer. The inset is the optical photograph of InSe transistor. (c) I-V curves of BN-encapsulated InSe transistor at different time. (d) The voltage-current characteristics of this transistor at the different gate voltages.

FIG. 9 (a) Transport characteristics of InSe transistor at different temperatures. (b) Mobility vs temperature (°C) for this device. (c) The bandgap alignment at the metal-InSe interface. Φ_m is the work function of metal. Φ_{SBH} is the Schottky barrier height. (d) Comparison of mobility of common 2D semiconductor materials.

near the metal-InSe interface, which is a typical Schottky contact. To further understand the influence of temperature, the relationship between the drain-source current (I_{ds}) and the Schottky barrier height (Φ_{SBH}) is given by thermal emission equation:⁴²

$$I_{ds} = A_{2d}^* T^2 \exp\left(\frac{q\Phi_{SBH}}{K_B T}\right) \left[1 - \exp\left(-\frac{qV_{ds}}{K_B T}\right)\right] \quad (4)$$

where A_{2d}^* is the equivalent Richardson constant, T is the temperature, k_B is the Boltzmann constant, q is the electronic charge, V_{ds} is the drain to source bias. Apparently, V_g is less than that of flat-band voltage (V_{FB}), the thermal emission current is dominated. Above the value of V_{FB} , thermally assisted tunnelling current is more important compared to thermal emission current. Moreover, as the temperature increases, the current I_{ds} also exhibits the same trend, as evidenced by FIG. 9(a). In general, most semiconductors demonstrate the band gap energy in the range from 0.2 to 3 eV, as shown in FIG. 9(d). However, they exhibit a various transport behaviour. For instance, PtSe_2 , MoTe_2 , and WSe_2 show a low mobility which is below $30 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$,^{40,41,43} which is similar to that of our InSe transistor. In addition, SnS_2 and MoS_2 exhibit a slightly larger value of $\sim 40\text{--}60 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$.^{44,45} However, our encapsulated InSe FET exhibits electron-dominated carrier transport with higher

mobility ($71.0 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$) at high temperature. Moreover, this device almost does not deteriorate after 2 months and even works well at high temperature of up to 200 °C. Our study may pave the way for sensitive semiconductors such as InSe in electrical and optoelectronic fields.

Conclusions

In summary, vertically aligned h-BN films have been deposited on Si wafer using HIPIMS with a pure boron source. Our results indicate that nitrogen gas plays a key role on the control of alignment and hence the thermal conductivity of the films. Moreover, as the nitrogen varies, the alignment of the films and its thermal conductivity exhibits the same trend which is associated to the stress in the as-grown films. Such oriented h-BN can be used a protective layer for InSe FETs which are not stable in typical environments and easily degraded. BN-encapsulated InSe transistor works well after 2 months and even performs at high temperature, with a high mobility of up to $71.0 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$. Our study suggests that the alignment engineering in h-BN samples is plausible for thermal performance enhancement. It further paves the way for sensitive semiconductors such as InSe in electrical and optoelectronic field.

Conflicts of interest

There are no conflicts to declare.

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