Thick GaN film stress-induced self-separation

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Cracking of thick GaN films on sapphire substrates during the cooling down after the growth was studied. The cracking was suppressed by increasing the film-to-substrate thickness ratio and by using an intermediate carbon buffer layer, that reduced the binding energy between the GaN film and the substrate. Wafer-scale self-separation of thick GaN films has been demonstrated.

I. INTRODUCTION

Gallium nitride substrate is the basis of modern high current density devices: high-voltage diodes and transistors [1, 2], light emitting diodes [3], vertical cavity surface emitting lasers [4], superluminescent light emitting diodes [5], high electron mobility transistors [6–8]. The main method for the production of GaN substrates today is the hydride vapor phase epitaxy growth of bulk GaN film on a foreign substrate, usually sapphire. An important step of the technological process with this approach is the separation of the bulk GaN film from the foreign substrate after growth, which is usually done by removing the substrate with laser lift-off [9, 10], or by stress-driven self-separation along the weakened interface between the substrate and the film [11, 12] or parallel to the interface [13–16]. Cracking of the GaN film during the cooling down and during the self-separation process is a significant problem, reducing the yield of the process. Crack-free cooling of GaN films on a sapphire substrate was obtained for films with a thickness of up to 300 µm, such films were then separated from the substrate using the laser lift-off method [9, 10]. Successful wafer-scale stress-induced self-separation has been reported for GaN films with a thickness of 3...5 millimeters [15], while cracking of GaN films with lower thickness was observed [13] unless special intermediate layers weakening the bonding between the film and the substrate are used [11, 12]. In this work, the processes of self-separation and cracking of thick GaN films on sapphire substrates are investigated, and the parameters for the reproducible crack-free self-separation are determined.

II. EXPERIMENTAL

A. Self-separation of GaN films on sapphire substrates

A set of more than 100 GaN films with a thickness from 100 µm to 5000 µm were grown on c-plane sapphire substrates with a thickness of 430 µm and a diameter of 52 mm (2 inch). The two-stage growth process was used to grow crack-free films with smooth surface [17]. No special substrate surface treatment to weaken the bonding between the substrate and the GaN film was employed.

The following typical failure modes were observed, depending on the thickness of the GaN film:

• No self-separation occurred and no cracks were generated inside GaN film and inside the sapphire substrate for GaN films with thickness less than ∼300 µm (fig. 1a).

Fig. 1. GaN films of various thicknesses $h_{GaN}$, grown on sapphire substrates with a thickness of 430 µm and a diameter of 52 mm: a) $h_{GaN}=200$ µm, no cracks can be observed in the GaN film and in the sapphire substrate, no signs of self-separation. b) $h_{GaN}=400$ µm, cracks in the GaN film and in the sapphire substrate were formed, no self-separation. c) $h_{GaN}=2000$ µm, GaN film self-separated from the sapphire substrate over the entire area, several cracks were formed in the GaN film dividing it into several pieces. d) $h_{GaN}=2800$ µm, GaN film self-separated from the sapphire substrate as a single piece.

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FIG. 2. A 365-µm thick GaN film, grown on a 430 µm thick sapphire substrate with a carbon buffer layer. a) The free-standing GaN film self-separated during the cooling down as a single piece. b) The sapphire substrate remained intact during the self-separation.

- Films with a thickness from ~300 µm to < 2500 µm cracked into multiple pieces (fig. 1b,c). Self-separation of the GaN film from the substrate was observed in a plane located inside the GaN film parallel to the interface. The separated area of the film increased with increasing film thickness – from the absence of separation for a 400-µm thick film to complete separation for a 2000-µm thick film.

- Films with a thickness higher than 2800 µm self-separated as a single piece without cracking (fig. 1d). The separation plane was located inside the GaN film at a distance of 200-400 µm from the interface.

B. Self-separation of GaN film on a sapphire substrate with a carbon buffer layer

GaN film with a thickness of 365 µm was grown epitaxially on a sapphire substrate with a thickness of 430 µm using a carbon buffer layer [18]. The carbon buffer layer was deposited by methane thermal decomposition process from a CH$_4$/H$_2$ mixture [19] at a deposition temperature of 1020 °C, a process pressure of 105 kPa and a CH$_4$ partial pressure of 1.3 kPa. The GaN film self-separated as a single piece during cooling down after the growth (fig. 2). Self-separation occurred along the interface of the GaN film and the substrate.

III. DISCUSSION

A. Crack types

The following types of cracks were observed in thick GaN films, grown on sapphire substrates, after cooling down: surface and channeling cracking of sapphire and GaN, sapphire debonding along the interface and sapphire debonding by spalling (fig. 3). The stress in the GaN film is compressive near the interface and tensile near the surface, and the stress in the sapphire substrate is tensile across the entire thickness. 

The values of a nondimensional driving force for crack formation $Z$ are given for the case of semi-infinite GaN film ($h_{GaN} \gg h_{sapphire}$) [20].

B. Stress distribution

To determine crack-free conditions for cooling and separation, the stress distribution in the GaN film and the sapphire substrate and the driving forces for crack formation were calculated.

The deformation and distribution of stresses in a sapphire substrate of radius $r$ and thickness $h_{sapphire}$, with the crack propagates inside the GaN film parallel to the interface at a depth at which the in-plane shear stress intensity factor $K_{II} = 0$ [21]. The steady-state spalling depth depends on the elastic mismatch between GaN and sapphire, and on the thicknesses of the GaN film and the sapphire substrate [21].

Sapphire debonding leads to self-separation of GaN film and is desirable or at least permissible. Surface crack formation in the GaN film results in cracking of the film into several parts during cooling down or during further processing and is completely unacceptable.

FIG. 3. Schematic representation of the stress distribution and the failure modes in a thick GaN film on a sapphire substrate ($h_{GaN} \gg h_{sapphire}$). The stress in the GaN film is compressive near the interface and tensile near the surface, the stress in the sapphire substrate is tensile across the entire thickness. The values of a nondimensional driving force for crack formation $Z$ are given for the case of semi-infinite GaN film ($h_{GaN} \gg h_{sapphire}$) [20].

FIG. 4. The stress in a GaN film on a sapphire substrate with thickness of 430 µm and diameter of 52 mm as a function of the GaN film thickness. When the GaN film thickness is lower than 300 µm, the stress in the GaN film is compressive and the formation of surface and channeling cracks in the GaN film is energetically unfavorable.
a GaN film of thickness $h_{GaN}$ were calculated by the minimization of the total strain energy, assuming that the solution of the problem has radial symmetry. Elastic properties of sapphire and GaN were assumed isotropic with the Young’s moduli of GaN and sapphire $E_{GaN} = 343$ GPa and $E_{sapphire} = 430$ GPa and the Poisson’s ratios $\nu_{GaN} = 0.21$ and $\nu_{sapphire} = 0.26$ \cite{24,25}.

The built-in strain $u_0$ was calculated taking into account the temperature dependence of the thermal expansion coefficients:

$$u_0 = \int_{T_0}^{T_g} (\alpha_{GaN}(T) - \alpha_{sapphire}(T)) \,dT$$

where $T_g$ is the growth temperature, $T_0$ is the room temperature $\alpha_{GaN}$ and $\alpha_{sapphire}$ are the thermal expansion coefficients of GaN and sapphire \cite{26,27}.

The components of the displacement vector in the interface plane were taken as trial functions:

$$v_r(r) = k_1r + k_4r^3$$

$$v_z(r) = k_2r^2 + k_4r^4$$

where $v_r$ - radial displacement component, $v_z$ - vertical displacement component, $k_1\ldots k_4$ - variation parameters. Kirchhoff’s hypothesis is used to approximate the displacement field:

$$u_r(r,z) = v_r - z \frac{\partial v_r}{\partial r}$$

$$u_z(r,z) = v_z$$

Nonlinear terms were taken into account when calculating the dependence of the strain tensors on the displacement vector in cylindrical coordinates:

$$u_{rr} = \frac{\partial u_r}{\partial r} + \frac{1}{2} \left( \frac{\partial u_r}{\partial r} \right)^2 + \frac{1}{2} \left( \frac{\partial u_z}{\partial r} \right)^2 + u_0$$

$$u_{\phi\phi} = \frac{u_r}{r} + \frac{1}{2} \left( \frac{u_r}{r} \right)^2 + u_0,$$

$$u_{zz} = -\frac{\nu}{(1-\nu)} (u_{rr} + u_{\phi\phi}),$$

$$u_{r\phi} = \frac{1}{2} \left( \frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial z} \frac{\partial u_z}{\partial r} + \frac{\partial u_z}{\partial r} \frac{\partial u_z}{\partial r} \right),$$

The stress tensor components and the specific elastic energy:

$$\sigma_{rr} = \frac{E}{1+\nu} \left( u_{rr} + \frac{\nu}{1-2\nu} (u_{rr} + u_{\phi\phi} + u_{zz}) \right),$$

$$\sigma_{\phi\phi} = \frac{E}{1+\nu} \left( u_{\phi\phi} + \frac{\nu}{1-2\nu} (u_{rr} + u_{\phi\phi} + u_{zz}) \right),$$

$$\sigma_{zz} = \frac{E}{1+\nu} \left( u_{zz} + \frac{\nu}{1-2\nu} (u_{rr} + u_{\phi\phi} + u_{zz}) \right),$$

$$\sigma_{r\phi} = \frac{E}{1+\nu} u_{r\phi},$$

$$U = \frac{E}{2(1+\nu)} ((u_{rr}^2 + u_{\phi\phi}^2 + u_{zz}^2 + 2u_{r\phi}^2) + \frac{\nu}{1-2\nu} (u_{rr} + u_{\phi\phi} + u_{zz})^2).$$

The total strain energy is obtained by integrating over volume:

$$F = \int_0^R \int_{-h_{sapphire}}^{h_{GaN}} U \,dV$$

The minimum potential energy $F$ is found from the solution of a system of nonlinear equations:

$$\frac{\partial F}{\partial k_i} = 0$$

Analytical expressions for the system of nonlinear equations \cite{16} were obtained using the computer algebra system \cite{28}. The numerical solution of the equation system \cite{16} was obtained using the Powell’s method \cite{29}. The results are shown in fig. \cite{3}.

C. Driving force for cracking

When the sapphire substrate thickness is $430 \mu m$ and the thickness of the GaN film is less than $300 \mu m$, the stress in the GaN film and on the sapphire substrate surface is compressive (fig. \cite{4}), and the formation of surface and channeling cracks in the GaN film and in the sapphire substrate is energetically unfavorable.

When the GaN film thickness is higher than $300 \mu m$, several competing cracking processes shown in fig. \cite{3} take place. What type of crack will arise first during the cooling process, depends on the distribution of the stress in the substrate-film structure. The driving force for cracking is the elastic strain energy

$$U = (1-\nu) \frac{E_f}{\sigma^2}$$
FIG. 5. The ratio of the substrate separation driving force to the GaN cracking driving force: \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \) on the thickness of the GaN film. The sapphire substrate thickness is 430 \( \mu \)m. Cracking of GaN films was observed at \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \lesssim 6 \), that corresponds to \( h_{\text{GaN}} \lesssim 2500 \) \( \mu \)m. Reproducible separation without cracking was observed at \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \gtrsim 8 \), that corresponds to \( h_{\text{GaN}} \gtrsim 2800 \) \( \mu \)m.

That is released during the crack formation. A crack of a certain type can propagate if the energy release rate for this type of crack \( G \) exceeds the surface energy of the formed crack \( \Gamma \):

\[
G = \frac{Z \sigma^2 h}{E_f} > \Gamma
\]

(18)

where \( Z \) is a dimensionless parameter depending on the crack geometry, \( \sigma \) – stress in the film, \( E_f \) – Young’s modulus of the film, \( h \) – crack length [20]. Sapphire substrate cracking and separation by debonding and spalling is determined by tensile stress in the substrate \( \sigma_{\text{sapphire}} \). Cracking of GaN film is determined by tensile stress on the GaN film surface \( \sigma_{\text{GaN}} \). The ratio of energy release rates for spalling and for GaN cracking \( \frac{G_{\text{spalling}}}{G_{\text{cracking}}} \) is proportional to \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \). With an increase in this ratio, it can be expected that the spalling crack will be initiated and complete self-separation of the substrate will occur before the stress on the surface of the GaN film exceeds the fracture resistance. The dependence of the stress ratio \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \) on the thickness of the GaN film at a sapphire substrate thickness of 430 \( \mu \)m is shown in Fig. 5. The stress ratio \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \) increases with increasing the GaN film thickness. Cracking of GaN films observed at \( h_{\text{GaN}} < 2500 \) \( \mu \)m corresponds to \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \lesssim 6 \). Reproducible separation without cracking observed at \( h_{\text{GaN}} > 2800 \) \( \mu \)m corresponds to \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \gtrsim 8 \).

Besides increasing the \( \frac{\sigma_{\text{sapphire}}^2}{\sigma_{\text{GaN}}^2} \) ratio by increasing the GaN film thickness, another way to promote self-separation is to reduce the binding energy between the film and the substrate. The surface energy of spalling crack in GaN is 6.7 J/m\(^2\) [30], the use of the carbon buffer layer reduces the binding energy to 0.27 J/m\(^2\) [31], which allowed to obtain wafer-scale self-separation of the GaN film with thickness of 365 \( \mu \)m (fig. 2).

IV. CONCLUSION

The thermal stress arising in a thick GaN film on a sapphire substrate during the cooling down after growth is the driving force of the GaN film cracking and the GaN self-separation. Crack-free freestanding GaN film can be obtained in several ways:

- Growing GaN film with thickness \( h_{\text{GaN}} \lesssim 300 \) \( \mu \)m. In this case, the stresses on the free surfaces of the GaN film and the sapphire substrate are compressive and the surface cracking process is energetically unfavorable. The laser lift-off method can be used to separate the GaN film from the sapphire substrate.
- Growing GaN film with thickness \( h_{\text{GaN}} \gtrsim 2800 \) \( \mu \)m. In this case, the stress in the sapphire substrate is significantly higher than the stress in the GaN film, and complete separation of the substrate by spalling occurs before the stress in the GaN film exceeds the fracture resistance.
- Growing GaN films on an intermediate layer with a low binding energy. For example, a crack-free self-separation of a 365-\( \mu \)m thick GaN film was demonstrated using a carbon buffer layer.

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