

# Application of selective area epitaxy for GaN devices

REGINA PASZKIEWICZ

The Faculty of Microsystem Electronics and Photonic, Wrocław University of Technology,  
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

The paper presents the overview of selective area epitaxy (SAE) and epitaxial lateral overgrowth (ELO) techniques of nitrides by metalorganic vapour phase epitaxy (MOVPE) and hydride vapour phase epitaxy (HVPE) on patterned sapphire, SiC and Si substrates. These techniques which allowed precise control of the size and shape of overgrown material, were applied to defect reduction in GaN epitaxial layers and to fabrication of optical and electronic devices. The selective maskless growth of GaN on the top of Si tips without mask are also presented as an example of SAE techniques.

## 1. Introduction

The basic idea of SAE was proposed by JOYCE *et al.* [1] for Si epitaxy on Si substrates in 1962. It was shown that SAE allowed precise control of the shape and size of overgrown material. Since then, selective epitaxy was widely used in heteroepitaxial systems such as GaAs/Si [2], InP/Si [3],  $\text{Ge}_x\text{Si}_{1-x}$ /Si and InGaAs/GaAs for obtaining epitaxial layers with extremely low dislocation density.

The GaN and AlGaN SAE on sapphire were demonstrated for the first time in 1994 by KATO *et al.* [4]. To achieve selected growth, the GaN must be deposited on the underlying GaN layer through the windows etched in a dielectric or metallic mask. The main problem in selective epitaxy is the difficulty in achieving true selectivity, with deposition occurring only in the mask openings and not on the mask. This depends on the growth process parameters such as temperature, pressure and reagent concentration in the epitaxial reactor. Both MOVPE and HVPE were used for nitrides layer deposition.

## 2. Selective area epitaxy of GaN

Three possible types of sidewalls geometry for stripe patterns can be obtained (Fig. 1) in the selective epitaxy of GaN. When the ratio of lateral to vertical growth rate is zero, then the stripes have the rectangular cross-section with the same width as the mask pattern (Fig. 1a).

The stripe with triangular cross-section (Fig. 1b) can be obtained when the vertical growth planes face out. In this case, the prolonged growth leads to coalescence by

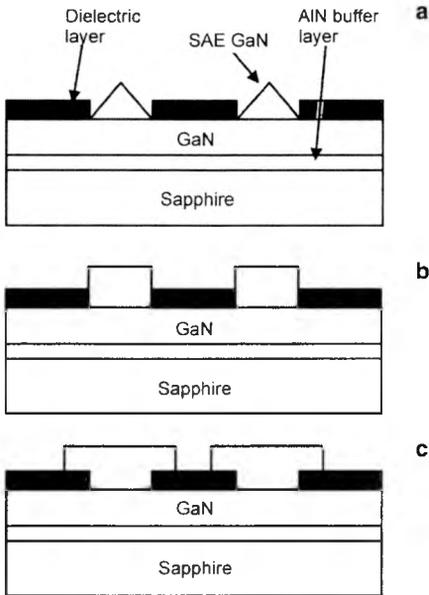


Fig. 1. Schematic diagram of the possible types of a selectively deposited stripe cross section: rectangular (a), triangular (b) and ELO (c).

growing of the side facets of the triangle, however, a non-planar surface is obtained. KAPOLNEK *et al.* [5] observed the anisotropy in GaN epitaxial lateral overgrowth which depended on the stripe pattern crystallographic orientation. The anisotropy was related to different growth velocities on different crystal planes.

In the case of nonzero ratio the deposition beyond the opening can be observed (Fig. 1c) leading to coalescence of selectively grown stripes after prolonged deposition. As a result, flat surface can be obtained. Such SAE process was called ELO (epitaxial lateral overgrowth). The first ELO GaN/sapphire growth using HVPE technique was performed by USUI *et al.* [6]. NAM *et al.* [7] applied the ELO technique to GaN growth on 6H-SiC substrate. The dislocation density reduction to the order of  $10^7 \text{ cm}^{-2}$  was observed in the material overgrown on the mask.

It was found that the GaN selective growth could be characterised by two extreme crystallographic orientations:  $\langle 11\bar{2}0 \rangle$  and  $\langle 1\bar{1}00 \rangle$  (Fig. 2).

The stripes oriented along  $\langle 11\bar{2}0 \rangle$  direction of GaN were inclined and bound by smooth  $\{1\bar{1}01\}$  facets under a wide range of growth process parameters and tended to exhibit low lateral growth rates  $V_L$ . The stripes oriented along the  $\langle 1\bar{1}00 \rangle$  direction could reveal a wide range of sidewall facets. Here the lateral growth rates depended on the growth process parameters and the fill factor (the ratio of open width to pattern period). The topology of such stripes was influenced mainly by the V/III molar ratio. At the low V/III molar ratio their sidewalls were inclined  $\{11\bar{2}2\}$  facets and the lateral growth was small. The smooth vertical facets  $\{11\bar{2}0\}$  appeared when the V/III molar ratio increased (in our experiments from 2500 to 5000). In this range the lateral growth

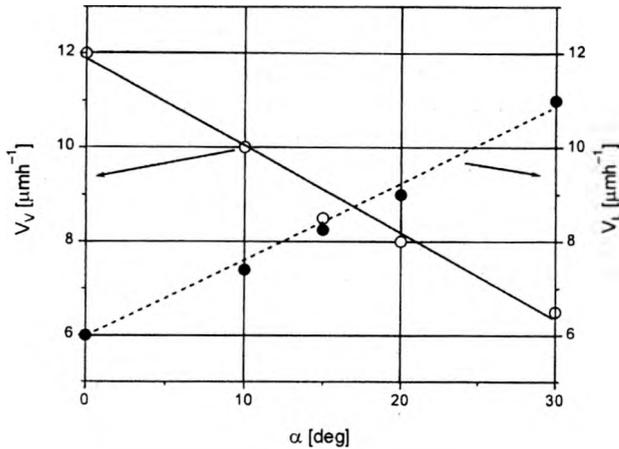


Fig. 2. Vertical and lateral growth rate of the stripes vs. angular displacement from  $\langle 11\bar{2}0 \rangle$  direction.

rates changed approximately linearly with the V/III molar ratio. Further increase in V/III molar ratio resulted in the formation of  $\{10\bar{1}1\}$  facets. The stripe sidewalls became rough and decrease in the lateral growth rate was observed.

It was found that SAE process was influenced by such mask parameters as: material [8], size [9], openings orientation [10], fill factor [11]; as well as the growth process parameters: reactor pressure [12], V/III molar ratio [13], growth temperature [14], carrier gas [15], impurity [16] and substrate [17], [18]. The influence of pressure and mask width is similar and opposite to the effect of temperature and V/III molar ratio. The topography of a selectively grown GaN stripe could be evaluated depending on its crystallographic orientation and deposition process parameters [19].

The selective GaN growth was also performed using the dot pattern (5  $\mu\text{m}$  diameter and 10  $\mu\text{m}$  space) [20]. Pyramid structures, each bounded by six  $\{1\bar{1}01\}$  facets, were observed. The structure was self-limited in size. It was caused by low growth rates of inclined  $\{1\bar{1}01\}$  facets compared to the (0001) plane, allowing non-infirmities in the growth rate to be overcome by structure self-limitation.

### 3. Device application of SAE

Because SAE allowed the spatially controlled growth of GaN through defined mask opening, this technique is promising for fabrication of GaN devices. The difficulties in GaN dry etching and cleaving were the reason for the use of SAE for laser cavity fabrication. Hexagonal microfacet (HMF) lasers were fabricated by electron cyclotron resonance (ECR) dry etching of as-grown planar InGaN multi-quantum wells (MQW) laser structures, followed by regrowth of p-GaN to form mirror facets of lasers. Stimulated emission was observed at 401 nm at room temperature by photopumping [21].

Also, rectangular cross-sectional GaN low-loss optical waveguides for active and passive photonic devices were deposited on sapphire. The stimulated emission from the optical waveguides was measured at 77 K using photopumping [22].

Figure 3 presents the GaN optical waveguides selectively grown on sapphire at Wrocław University of Technology, Poland. The waveguides, with rectangular cross-sectional shape, comprising (0001) and  $\{10\bar{1}1\}$  facets were fabricated using 5  $\mu\text{m}$  diameter and 10  $\mu\text{m}$  space stripe pattern. The smooth and flat crystal facets were obtained due to MOVPE growth process parameters selection. The successful realisation of optical waveguides will enable the GaN micro- and optoelectronic devices integration.

The interconnected  $\mu$ -disk LEDs based on InGaN/GaN based on single quantum wells (SQW) were fabricated by SAE technique [23]. A significant increase in quantum efficiency in  $\mu$ -disk LEDs, of more than 60% over the conventional LEDs of the same area, was achieved as a result of enhancements in internal quantum efficiency and extraction efficiency in these devices.

The GaN/4H-SiC n-p-n heterojunction bipolar transistor (HBT) was fabricated [24]. The device structure consisted of n-SiC collector, p-SiC base structure and n-GaN emitter selectively grown through a SiO<sub>2</sub> mask. The transistor action in these devices was observed in the temperature range from room temperature to 300 °C. The maximum current density of 500 A/cm<sup>2</sup> at power density of 7.5 kW/cm<sup>2</sup> was measured.

The wide bandgap, mechanical hardness, negative electron affinity of AlN and AlGaN and low positive electron affinity of GaN make them highly promising for electron field emission devices. The field emission from GaN hexagonal pyramids on GaN/sapphire was observed for the first time by UNDERWOOD *et al.* [25]. The arrays of single crystal GaN pyramids were grown selectively through a dielectric mask by MOCVD method. The pyramids were biased negatively with respect to a metal anode and the emission current of 0.8  $\mu\text{A}$  at 2 kV was observed.

Another technique was developed at Wrocław University of Technology. In this method the array of Si emitters was covered by selectively deposited GaN layers [26]. The conditions of MOCVD process were selected so as to allow GaN deposition only on the top of pyramids, not on their inclined side walls. Maskless process was used. Figure 4 shows a SEM image of the array of Si emitters with GaN deposit on the top. The measurements of  $I$ - $V$  characteristic of the 1×1 mm<sup>2</sup> array, consisting of 42×42 emitters, resulted in an emission current of 2 mA at 2.5 kV. It was observed that the Fowler–Nordheim plot ( $\log(I/V^2)$  vs.  $1/V$ ) had a linear shape with a negative slope, which confirmed the occurrence of the field emission mechanism. The use of Si substrates is beneficial from the application point of view because of their large size, low cost and the prospects of the integration of GaN based and Si based devices. As opposed to sapphire, the Si substrate is conducting which makes the backside electrical and thermal contact processing possible.

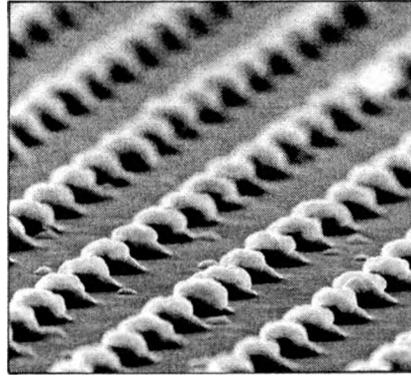
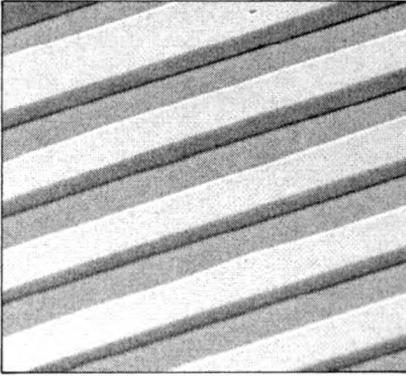


Fig. 3. SEM images of rectangular cross-sectional GaN waveguides.

Fig. 4. SEM images of the array of 42x42 Si emitters covered with GaN.

The SAE process, which permitted the growth of selective structures with a triangle cross-section, was selected for growing the regular arrays of low dimensional structures (*i.e.* quantum wires and dots) of nitrides [27]. Such structures can be used in realisation of new low dimensional nitride based photonic devices.

Currently, the main area of SAE application is, however, the pseudo-bulk GaN substrate fabrication. The large differences in lattice constants, thermal expansion coefficients and chemical nature between GaN and sapphire (SiC) substrates cause the formation of threading dislocation with density  $10^8$ – $10^{10}$   $\text{cm}^{-2}$ , during heteroepitaxial layers deposition. Many efforts have been made to minimise the dislocation density influence on the performance of GaN based devices. The use of pseudo-bulk GaN substrates produced by ELO, which is a particular case of SAE technique, is the most promising one. This technique was proposed by NISHINAGA *et al.* [2] who obtained GaAs layers with extremely low dislocation density by liquid phase epitaxy on GaAs using  $\text{SiO}_2$  lithographically patterned mask. The pseudo-bulk GaN substrates were obtained by performing a regrowth on a conventional GaN layer, deposited on sapphire and selectively masked by an amorphous layer so that the dislocation under the mask could not propagated into the overgrown layers [16]. The use of such substrates for subsequent GaN based device structures deposition resulted in the improvement of the parameters of the devices, in comparison with the identical structures grown on sapphire. Several variants of ELO techniques were proposed for the following purposes: FIELO (facet initiated ELO) [6], PENDEO epitaxy [28], FACELO (facet controlled ELO) [29], utilisation of other masks as tungsten [30], air-bridge ELO [31], use of grooved stripes [32] and direct lateral epitaxy [33]. A remarkable defect reduction (to  $\leq 10^5$   $\text{cm}^{-2}$ ) was demonstrated for GaN layers grown on sapphire and SiC, using these techniques. The one-step and two-step ELO processes, based on the control of GaN structures by changing the growth condition during the growth process, were

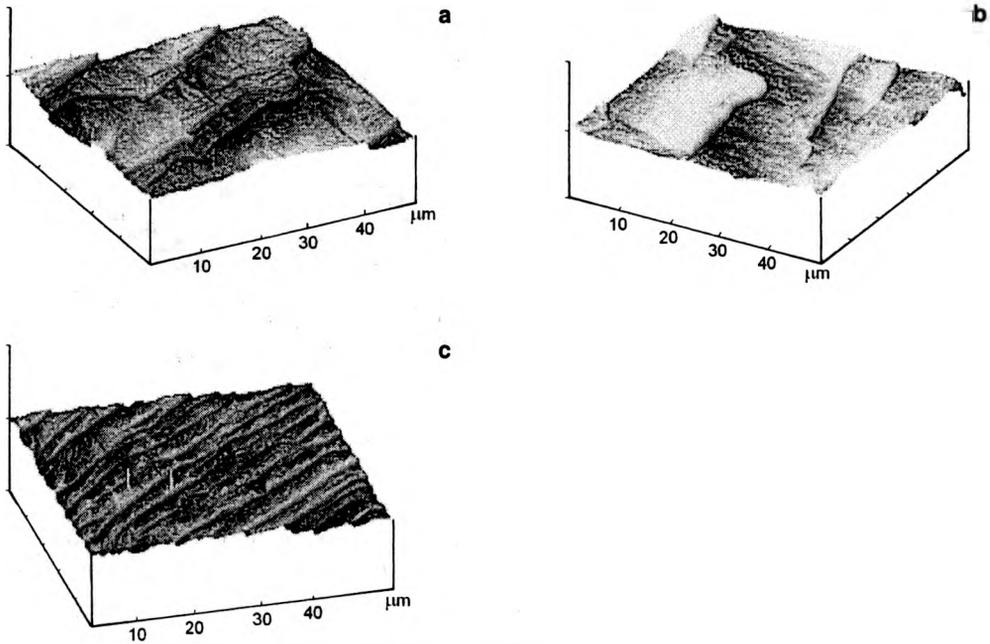


Fig. 5. AFM images of: GaN/sapphire (a), one-step ELO GaN (b), two-step ELO GaN (c). Vertical scale – 10 nm.

employed at Wrocław University of Technology, for the GaN pseudo-bulk substrate preparation [34]. The  $12\ \mu\text{m}$  periodic gratings and  $6\ \mu\text{m}$  wide stripes oriented along the  $\langle 1\bar{1}00 \rangle$  direction were selected, and the MOVPE process parameters were chosen to maximise the lateral growth rate and sidewalls smoothness. Figure 5 presents the comparison of morphology of GaN layers grown on sapphire by one- and by two-step ELO process. It was observed that the two-step ELO process offers the superior morphology of GaN layers in addition to the defect density reduction to the level of the order of  $10^6\ \text{cm}^{-2}$ .

#### 4. Summary

The selective area epitaxy and epitaxial lateral overgrowth techniques of nitrides were reviewed for the regrading their potential application to optical and electronic devices. The parameters influencing the change in the morphology of selectively grown structures were selected and discussed. The GaN selective growth experiments performed at Wrocław University of Technology, Poland, were presented.

*Acknowledgments* – This work was supported partially by Polish Science Foundation (Project TECHNO 106/2000, TECHNE 6/2001) and Wrocław University of Technology – Advanced Materials and Nanotechnology Centre.

## References

- [1] JOYCE B.D., BRADLEY J.A., *Nature* **195** (1962), 458.
- [2] NISHINAGA T., NAKANO T., ZHANG S., *Jpn. J. Appl. Phys., Pt. 2* **27** (1988), L964.
- [3] PARILLAUD O., GIL-LAFON E., GERARD B., ETIENNE P., PRIBAT D., *Appl. Phys. Lett.* **68** (1996), 2654.
- [4] KATO Y., KITAMURA S., HIRAMATSU K., SAWAKI N., *J. Cryst. Growth* **144** (1994), 133.
- [5] KAPOLNEK D., KELLER S., VETURY R., UNDERWOOD R.D., KOZODOY P., DENBAARS S.P., MISHRA U.K., *Appl. Phys. Lett.* **71** (1997), 1204.
- [6] USUI A., SUNAKAWA H., SAKAI A., YAMAGUCHI A., *Jpn. J. Appl. Phys. Pt. 2* **36** (1997), L899.
- [7] NAM O.H., BREMSER M.D., ZHELEVA T.S., DAVIS R.F., *Appl. Phys. Lett.* **71** (1997), 2638.
- [8] HIRAMATSU K., HAINO M., YAMAGUCHI M., MIYAKE H., MOTOGAITO A., SAWAKI N., IYETIKA Y., MAEDA T., *Mater. Sci. Eng. B* **82** (2001), 62.
- [9] LI X., BISHOP S.G., COLEMAN J.J., *Appl. Phys. Lett.* **73** (1998), 1179.
- [10] PARK J., GRUDOWSKI P.A., EITING C.J., DUPUIS R.D., *Appl. Phys. Lett.* **73** (1998), 333.
- [11] MARCHAND H., IBBERSTON J.P., FINI P.T., WU X.H., GOLAN Y., VENTURY R., PARISH G., KOZODOY P., TARSIA E.J., KELLER S., DENBAARS S.P., SPECK J.S., MISHRA U.K., [In] *Proc. 8th European Workshop on MOCVD and Related Growth Techniques*, [Ed] K. Zaveta, V. Gregor, Institute of Physics, Ac. Sci. Czech Republic, Prague 1999, pp. 3–6.
- [12] HIRAMATSU K., NISHIYAMA K., ONISHI M., MIZUTANI H., NARUKAWA M., MOTOGAITO A., MIYAKE H., IYETIKA Y., MAEDA T., *J. Cryst. Growth* **221** (2000), 316.
- [13] IBBERSTON J.P., MARCHAND H., FINI P.T., WU X.H., KELLER S., DENBAARS S.P., SPECK J.S., MISHRA U.K., [In] *40th Electronic Materials Conference*, Charlottesville, VA, June 24–26, 1998.
- [14] ZHANG R., ZHANG L., HANSEN D.M., BOLESZAWSKI M.P., CHEN K.L., LU D.Q., SHEN B., ZHENG Y.D., KUECH T.F., [In] *GaN and Related Alloys*, [Eds.] S.J. Pearton, C. Kuo, A.F. Wright, T. Uenoyama, Materials Research Society, Warrendale, PA, USA 1999, p. G4.7.
- [15] TADATOMO K., OHUCHI Y., OKAGAWA H., ITOH H., MIYAKE H., HIRAMATSU K., [In] *GaN and Related Alloys*, [Eds.] S.J. Pearton, C. Kuo, A.F. Wright, T. Uenoyama, Materials Research Society, Warrendale, PA, USA 1999, p. G3.1.
- [16] BEAUMONT B., VAILLE M., NATAF G., BOUILLE A., GUILLAUME J.-C., VENNEGUES P., HAFFOUZ S., GIBART P., *MRS Internet J. Nitride, Semicond. Res.* **3** (1998), 20.
- [17] RAZEGHI M., KUNG P., WALKER D., HAMILTON M., DIAZ J., *Proc. SPIE* **3725** (1999), 14.
- [18] JOHNSON YU.A., BROWN J., MASRY N., MUTH J.F., COOK J., SCHETZINA J., HABERERN, KONG H., EDMOND J., *MRS Int. J. Nitride Semicond. Res.* **4S1** (1999), G4.3.
- [19] MARCHAND H., IBBERSTON J.P., FINI P.T., WU X.H., KELLER S., DENBAARS S.P., SPECK J.S., MISHRA U.K., *MRS Internet J. Nitride, Semicond. Res.*, **4S1** (1999), G4.5.
- [20] KITAMURA S., HIRAMATSU K., SAWAKI N., *Jpn. J. Appl. Phys., Pt. 2* **34** (1995), L1184.
- [21] AKASAKA T., ANDO S., NISHIDA T., SAITO H., KOBAYASHI N., *Appl. Phys. Lett.* **79** (2001), 1414.
- [22] TANAKA T., UCHIDA K., WATANABE A., MINAGAWA S., *Appl. Phys. Lett.* **68** (1996), 976.
- [23] JIN S.X., LI J., LIN Y., JIANG H.X., *Appl. Phys. Lett.* **77** (2000), 3236.
- [24] TORVIK J.T., LEKSONO M., PANKOVE J.I., VAN BROECK B., *MRS Internet J. Nitride, Semicond. Res.*, **4S1** (1999).
- [25] UNDERWOOD R.D., KAPOLNEK D., KELLER B.P., KELLER S., DENBARRS S.P., MISHRA U.K., *Solid State Electron.* **41** (1997), 243.
- [26] CZARCZYNSKI W., ŁASISZ S., MORAW M., PASZKIEWICZ R., TŁACZALA M., ZNAMIROWSKI Z., *Appl. Surf. Sci.* **151** (1999), 63.
- [27] ZHANG X., DAPKUS P.D., RICH D.H., KIM I., KOBAYASHI J.T., KOBAYASHI N.P., *J. Electron. Mater.* **29** (2000), 10.
- [28] ZHELEVA T.S., SMITH S.A., THOMSON D.B., GEHRKE T., LINTHICUM K.J., RAJAGOPAL P., CARLSON E., ASHMAWI W.M., DAVIS R.F., [In] *GaN and Related Alloys*, [Eds.] S.J. Pearton, C. Kuo, A.F. Wright, T. Uenoyama, Materials Research Society, Warrendale, PA, USA 1999, p. G3.38.

- [29] HIRAMATSU K., NISHIYAMA K., ONISHI M., MIZUTANI H., NARUKAWA M., MOTOGAITO A., MIYAKE H., IYECHIKA Y., MAEDA T., *J. Cryst. Growth* **221** (2000), 316.
- [30] SONE H., NAMBU S., KAWAGUCHI Y., YAMAGUCHI M., MIYAKE H., HIRAMATSU K., IYECHIKA Y., MAEDA T., SAWAKI N., *Jpn. J. Appl. Phys., Pt. 2* **38** (1999), L356.
- [31] KIDOGUCHI I., ISHIBASHI A., SUGAHARA G., TSUJIMURA A., BAN Y., *Jpn. J. Appl. Phys., Pt. 2* **39** (2000), L453.
- [32] ISHIDA M., OGAWA M., ORITA K., IMAFUJI O., YURI M., SUGINO T., ITOH K., *J. Cryst. Growth* **221** (2000) 345.
- [33] ZHANG X., LI R.R., DAPKUS P.D., RICH D.H., *Appl. Phys. Lett.* **77** (2000), 2213.
- [34] PASZKIEWICZ R., KORBUTOWICZ R., PASZKIEWICZ B., RADZIEWICZ D., TŁACZAŁA M., [In] *Proc. 23 International Spring Seminar on Electronic Technology, May 6–10, 2000, Balatonfüred, Hungary*, p. 263.

*Received May 13, 2002*