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Recent advances in InN-based III-nitrides towards novel nanostructure photonic devices

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1. Introduction

Bonding between In and N is weaker and longer than those for GaN and AlN, and this results in large mismatches for InN in both lattice parameters and optimum epitaxy temperatures among III-nitrides. Another important issue for InN epitaxy is a big expected difficulty in achieving p-type conduction, because the Fermi level stabilized energy for InN is located inside the conduction band, resulting in easy introduction of donor levels together with high density surface electrons.

Considering the above mentioned nature of InN, many people have paid attentions on 1) epitaxy for growing higher-quality and/or controlled-quality InN and In-rich InN-based alloys by MBE and MOVPE, 2) understanding/analyses on their "real" material parameters as well as inherent surface/interface properties, 3) understanding and reduction of residual donors, 4) p-type doping and hole conduction properties, and 5) examinations on potential application for photonic/electronic devices based on their inherent material properties/features of InN and In-rich InN-based alloys.

We also have been studying for a long time on the epitaxy and material control of InN and related alloys for both In-polarity and N-polarity growth regimes on c-plane GaN template as well as on c-sapphire. Significant progress has been made in the epitaxy control and material control including p-type doping of InN-based III-nitrides by MBE as well as the fabrication of their novel nanostructures. Details in epitaxy control of InN including its in-situ and real time monitoring [1, 2], successful p-type doping and related issues [1-7], and fabrication and characterization of InN-based nano-heterostructures are given in previously reported literatures [1, 2, 8-11].

In this talk/paper, we report the latest advances in InN epitaxy and material control paying special attention to the realization and characterization of novel InN/GaN MQWs consisting of around one monolayer (1ML)-thick InN wells in GaN matrix, together with in-situ and real-time SE characterization of self-limiting and self-ordering deposition processes resulting in 2ML, 1ML, and fractional ML InN wells in GaN matrix at extremely high temperatures under the In-polarity growth regime.

2. Proposal and features of novel InN-based QWs embedded in GaN

As one of the ideas to solve the problems when fabricating fine structure InN-based nano-heterostructures with quite sharp and flat hetero-interface in spite of highly lattice- and epitaxy-temperature mismatched system, we have proposed a novel structure InN/GaN QWs in which the basic structure is consisting of "1ML-thick" InN wells embedded in GaN matrix formed under +c-polarity growth regime.

Figure 1 shows a sub-Å resolution Z-contrast image obtained by using a scanning TEM for the sample grown at 650 °C. First, it has been confirmed in the Z-contrast image that the QW is coherently embedded and no defects are generated at the hetero-interface. Further, the localization of the extra intensity in the Z-contrast image appears to indicate the presence of a single layer of InN in the GaN matrix, although additional analysis is required for such thin layers as this 1 ML QW.

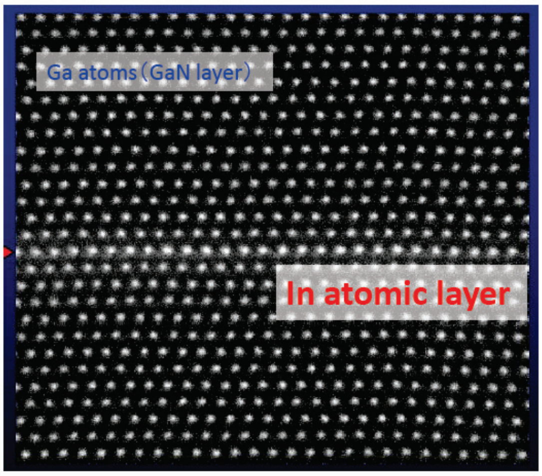

Fig.1 STEM-Z contrast image for 1 ML InN in GaN [2].

There are several features expected for the proposed novel InN-based QWs:

(1) Coherent growth of InN wells on GaN: Fabrication of high quality QWs can be expected in principle.

(2) GaN matrix effect for In-polarity InN deposition:

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Growth temperature for 1ML InN on GaN can be extremely higher than that for thick In-polarity InN deposition. The critical epitaxy temperature for In-polarity InN is 500 °C, but such thin InN layer as about 1 ML can be deposited even at temperatures up to 680 °C.

(3) Immiscibility between InN and GaN: Atomically flat and sharp 1 ML InN wells can be deposited on Ga-polarity GaN template by self-ordering and self-limiting processes under wider growth windows. The self-limiting growth is possible only for about 1 ML-thick InN deposition when the deposition temperatures are higher than the critical epitaxy temperature, i.e. 500 °C for the In-polarity InN deposition.

We first examined to fabricate a series of InN/GaN QWs at different growth temperatures from 500 °C to 650 °C with 50 °C step. As stated above, the highest growth temperature for "thick" In-polarity InN was about 500 °C, and the temperatures examined here were much higher than this critical temperature. It was found, however, that quite thin around 1 ML-thick InN deposition on Ga-polarity GaN template was possible even for just 1ML InN supply when the growth temperatures were between 500 °C and 600 °C. Here the "1ML InN supply" means that the In and N species corresponding to 1ML-thick InN deposition for the case of lower growth temperatures than 500 °C were supplied. When the growth temperature was further highered up to 650 °C, about 3 ML InN total supply under increased supply rate was necessary to assure the InN deposition. Furthermore, it was confirmed that the structural quality of obtained InN/GaN QWs was significantly improved with increasing growth temperature. As for the thickness control of InN wells, it was confirmed that the deposition of InN wells up to 2MLs was possible. When the InN wells were deposited at temperatures above 650 °C, fabrication of fractional ML InN wells was also possible, i.e., InN tended to be not a continuous layer because of lowered sticking coefficient for In and N species at such high temperature as 650 °C and/or enhanced dissociation and re-evaporation of InN at this high temperature.

It was confirmed that the PL emission around ~390 nm can be observed for the samples with 1 ML-thick InN QWs. Luminescence properties of the proposed novel structure InN/GaN QWs are basically following the behaviors and/or properties of GaN-based excitons localized at very thin and deep InN potential wells. Considering these together with discretely changing PL-peak behaviors, we have concluded at this moment that the longer wavelength side PL emissions around 420-430 nm are originating from 2 ML-thick InN QWs in a GaN matrix. Moreover, due to the effect of increased oscillator strength for such excitons effectively localized at ultimately thin InN wells, strong luminescence nature is expected for the proposed QWs, and detailed study for analyzing emission mechanism is underway now.

Experimental LED structure was fabricated and its fundamental performance was characterized to confirm the potential application of the proposed novel InN-based QWs for blue-green color light emitting devices. Since the well layer is ultimately thin in the proposed QWs, the QCSE (quantum confined Stark effect) is expected to be also ultimately minimized. In fact, we have confirmed in experimental LED structures consisting of 2ML-thick InN wells that very bright EL emission was observed at around 418 nm and only small blue shift from 418 nm to 416 nm was observed for two orders different current injection levels varied from 1 mA to 100 mA.

In order to achieve more longer wavelength EL emissions up to green, we have extended our understanding for the 1ML InN/GaN QWs to the asymmetric structure GaN/1-ML InN/InGaN/GaN QWs. We have confirmed that this structure is effective to extend the emission wavelength to longer side even though the InN well thickness is just 1 ML. We have succeeded in fabricating LEDs working at around 500 nm and detailed characterization for the performance of the LEDs is underway now.

3. Conclusions

We have proposed a novel structure InN-based QWs consisting of 1 ML-thick InN wells embedded in GaN matrix. The QWs can be fabricated at extremely higher temperatures than that for normal InN deposition, resulting in quite high quality QWs with no newly introduced misfit dislocations at the hetero interface. The fundamental properties of the novel InN-based nanostructures including asymmetric one have been confirmed to possess high potentiality for photonic device applications.

References

Epitaxy issues and Achieving p-type InN:

[1] A. Yoshikawa, S. B. Che, N. Hashimoto, H. Saito, Y. Ishitani, and X. Q. Wang, J. Vac. Sci. Technol. B 26 (2008) 1551.

[2] A. Yoshikawa, S. B. Che, Y. Ishitani, and X. Q. Wang, J. Crystal Growth 311 (2009) 2073.

[3] X. Wang, S.B. Che, Y. Ishitani, A.Yoshikawa, Appl. Phys. Lett. 90 (2007) 151901.

[4] X. Wang, S. B. Che, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Lett. 90 (2007) 201913.

[5] X. Wang, S. B. Che, Y. Ishitani, A. Yoshikawa, H. Sasaki, T. Shinagawa, and S. Yoshida, Appl. Phys. Lett. 91 (2007) 081912.

[6] X. Wang, S. B. Che, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Lett. 91 (2007) 242111.

[7] X. Wang, S. B. Che, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Lett. 92 (2008) 132108.

Fabrication and characterization of InN-based nanostructures:

[8] A. Yoshikawa, S. B. Che, W. Yamaguchi, H. Saito, X. Q. Wang, Y. Ishitani, Appl. Phys. Lett. 90 (2007) 073101.

[9] X. Wang, S.B. Che, Y. Ishitani, A. Yoshikawa, J. Cryst. Growth 301/302 (2007) 496.

[10] E. S. Hwang, S. B. Che, H. Saito, X. Q. Wang, Y. Ishitani, A. Yoshikawa, J. Elect. Materials 37 (2008) 597.

[11] S. B. Che, A. Yuki, H. Watanabe, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Exp. 2 (2009) 021001.