Application for Charlotte Ida Litman Tubis Award

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Photoluminescence of non-polar Nitride Semiconductors

Light-emitting diode (LED) has been used in many places in our life. Due to its energy saving and high lighting efficiency, the invention of blue LED with high lighting efficiency has been awarded 2014 Nobel Prize in Physics. The major material used to build a LED is Nitride material. Besides LED, many other types of optical electronic devices are also based on Nitride material. Therefore, the research about Nitride material attracts much attention.

The electrical conductivity of Nitride material is between that of a conductor and an insulator. Thus, Nitride material is always called Nitride semiconductor. There is a vast number of electrons inside a semiconductor. They have interactions with nuclei and the structure of the crystal, or among themselves. The interaction restricts the energy electrons may contain, hereby limiting the movement and locations of the electrons. Thus, in Condensed Matter Physics, the energy of electrons are more often used to describe the state of electrons, and an energy band structure can be depicted to show the energy range which electronic states are within. However, it is found in many types of semiconductors that there is always an energy gap where no electronic states can exist, and this gap is called band gap, as shown in Figure 1 (a). The band gap divides the band structure diagram into 2 parts. The lower low energy part is called "valence band", which is generally occupied by electrons, while the upper high energy part is called "conduction band", which is always vacant and can be occupied by electrons. The band gap differs from material to material. For commonly used Nitride semiconductors, like Gallium Nitride (GaN), Aluminum Nitride (AlN), Indium Nitride (InN), and their ternary (like $In_xGa_{1-x}N$) or quaternary ($Al_xIn_yGa_{1-x-y}N$) compounds, the band gap ranges from ~0.7eV (InN) to ~6.2eV (AlN).

Given optical or electrical excitations, the electrons in semiconductors can transit from one energy state to another, and the transition can absorb or emit photons. For example, as shown in Figure 1 (a), if we excite the electrons from valence band to conduction band, we will leave vacancies in valence band and they are called holes. The excited electrons will move to the bottom of the conduction band, and then transit over the band gap back to the vacancies in the valence band. The name of the process is recombination of electrons and holes. The transition is called interband transition and usually emits light. This type of transition is what LED lighting is based on. For Nitride semiconductors, as mentioned earlier, the band gap is within a large range from ~0.7eV to ~6.2eV. Thus, a large conduction band offset can be achieved by growing 2 different types of Nitride semiconductor together, as shown in Figure 1 (b). The structure is called a quantum well. Several energy states can be confined inside the quantum well due to the large band offset. Then electrons can just transit between high energy states and low energy states. This transition is called intersubband transition. The wavelength of the absorbed or emitted light from the transition is generally within the infrared range, so the intersubband transition is widely used for the design of infrared optical electronic devices.

Although there are many achievements in the research of Nitride semiconductors, there are still so many challenges to overcome, for the improvement of material quality and the performance of devices. For example, a higher recombination/transition rate is always pursued so that a higher lighting efficiency can be achieved. Each energy state is depicted by a wave function shown in Figure 2. The overlap between

different wave functions determines the recombination rate. However, if the band structure is like what is shown in Figure 2 (a), the overlap is significantly reduced. In fact, this is due to the asymmetry of the semiconductor crystal structure. The real structure is not like a cube, so if atoms are grown on some facet, the polarity formed by layers of different atoms causes such a tilted band structure. This structure is called polar structure. Many current commercial Nitride devices have this polar band structure, which hinders achieving higher lighting efficiency. To solve this problem, a non-polar band structure is proposed. This band structure is symmetrical and can be obtained by growing atoms on some specific facet. So far, to grow a homogeneous non-polar structure is still very challenging by current growth techniques in the world. Also, the design scheme of polar semiconductors does not work for non-polar semiconductors. Furthermore, in order to build a real device, we always need to grow and replicate many nanostructures. However, usually more than one semiconductor material is used to form the nanostructures, and different material has different sizes of crystal structure. Thus, there is strain in the structure and can be accumulated after many nanostructures are grown. The nanostructures are always grown layer by layer, and the top layers will have very bad quality due to the accumulation of strain. Sometimes more nanostructures may even fail to be grown after just growing the first several nanostructures. On the other hand, the strain can create many defects, which act like drains for electrons. Then electrons will not be successfully excited to the higher energy state to trigger lighting, and the lighting efficiency of the device will drop drastically. Therefore, the strain will affect the performance of devices significantly. We try to balance the strain between InGaN and GaN, and the strain between GaN and AlGaN, to reduce the effect of strain, so we propose a strain-balanced structure containing InGaN and AlGaN grown on GaN. We can adjust the size of each material as well as the In and Al composition to balance the strain. To date, the growth of non-polar structure containing InGaN and AlGaN with high quality is not well known. How to design devices on this structure to achieve better performance is still being explored. Thus, my research is to investigate a non-polar InGaN/AlGaN material system, aiming at finding a good growth procedure and design of the structure. The result of my research will help figure out how to achieve higher efficiency than current commercial devices by using non-polar Nitride semiconductors. Some challenging problems like efficiency droop (efficiency saturates or decreases when higher current is injected) or green gap (high efficiency in a wavelength range of 500nm – 550nm) can be expected to be solved by using non-polar Nitride semiconductors with high quality. My research will contribute to the commercial use of non-polar Nitride semiconductors.

I mentioned that there can be emitted light in both interband transitions and intersubband transitions. As a matter of fact, by analyzing the properties of the emitted light, like wavelength, linewidth or lighting efficiency, we can obtain information about the structures we grow. Both transitions can be triggered after optical or electrical excitation is applied to the semiconductor. If the excitations are optical, the phenomenon that light is emitted from interband transition is called photoluminescence (PL). Since it is not difficult to apply optical excitation to a sample, and the PL signal is acquired very fast and easily, the PL spectrum is widely used to analyze the quality of material. In my research, I use PL measurement to investigate the non-polar InGaN/AlGaN material system.

We first grew a series of 30nm non-polar InGaN semiconductors with different In compositions. By analyzing PL spectra, we find that the InGaN with about 9%-11% In gives most strong PL intensity compared with other In compositions. When the In composition is larger than 11%, the higher In composition is, the weaker the PL intensity is obtained. If the In composition is larger than 16%, the PL intensity is very weak and hard to collect. As temperature increases, PL intensity decreases dramatically for all samples. These phenomena show that many defects have been introduced into the semiconductor

and reduce the rate of interband transitions, especially for InGaN with high In composition. The low temperature applied in our growth technique is the reason why many defects are introduced. Furthermore, we observed a large discrepancy up to 200meV between experiment and simulation, which indicates that the distribution of In is not uniform. The non-uniform of In distribution has been confirmed in the structures grown by other major growth techniques, such as Metal-Organic Chemical Vapor Deposition. And now we have confirmed that the non-uniform distribution of In also exists in the structures by our growth technique, Plasma Assisted Molecular Beam Epitaxy. This shows that the non-uniform distribution cannot be avoided by current major growth techniques in the world. However, we have achieved a significant decrease of about 30% in terms of the linewidth of PL spectra when compared with previously reported values, which shows that the degree of non-uniform is less than that in the structures grown by other techniques. The achievement of more uniform distribution of In will reduce the efficiency droop and improve the efficiency by 10%.

After we succeeded in growing non-polar InGaN semiconductors with low defect for some low In compositions, we grew a series of AlGaN/InGaN superlattices. The In composition is within 9%-11%, and the Al composition and size of each quantum well are set accordingly to create a strain-balanced structure. A superlattice contains a large number of replicated quantum wells. The replication is aimed to improve optical or electrical signals. By analyzing the PL spectra, we observed a larger discrepancy between experiment and simulation than that for InGaN semiconductors, while there is little discrepancy for AlGaN/GaN superlatices. This indicates that the incorporation of In is the major reason for the discrepancy. The large discrepancy comes from the non-uniform distribution of In. Since the low temperature we used in our growth of InGaN introduces many defects, it is not surprising that PL intensity of these superlattices decreases dramatically as temperature increases. However, the linewidth has a different story. The broadening mechanism in superlattices is more determined by the structures. Given same size and same Al composition of AlGaN/GaN and AlGaN/InGaN, the PL linewidth is almost the same. Even though we measured the PL sepctra for AlGaN/InGaN with different In compositions up to 16%, as long as the size is the same, the linewidth of each PL spectrum is close to each other. Therefore, the incorporation of In and In composition fluctuations will not affect much the linewidth of PL spectra for superlattices. It is the first time that the linewidth is found to be not affected by In incorporation or the inhomogeneity of In distribution. This will help the design of non-polar Nitride superlattices for higher wavelength stability.

In current research, we keep improving our growth and have just found that adding more In than expected in the growth process can help reduce the interface roughness of the superlattices, resulting a narrower PL linewidth. We are also working on how to minimize the non-uniform distribution of In. Due to the In composition fluctuation, the bottom of conduction band or valance band will not be flat (Figure 3). The excited electrons will reach the minimum energy state and then trigger the interband transition. The “trap-like” structure is called potential minima. The size of it is called potential depth. By applying a widely used model proposed by Eliseev *et al* (Appl. Phys. Lett. 71, 569 (1997)) to analyze our PL spectra, we realize that we can achieve a small potential depth of ~13meV, while previous reported values are around 46meV. This small potential depth is even obtained in material with high In composition (>10%) we grew, which is helpful for achieving high efficiency in the wavelength range of green light.

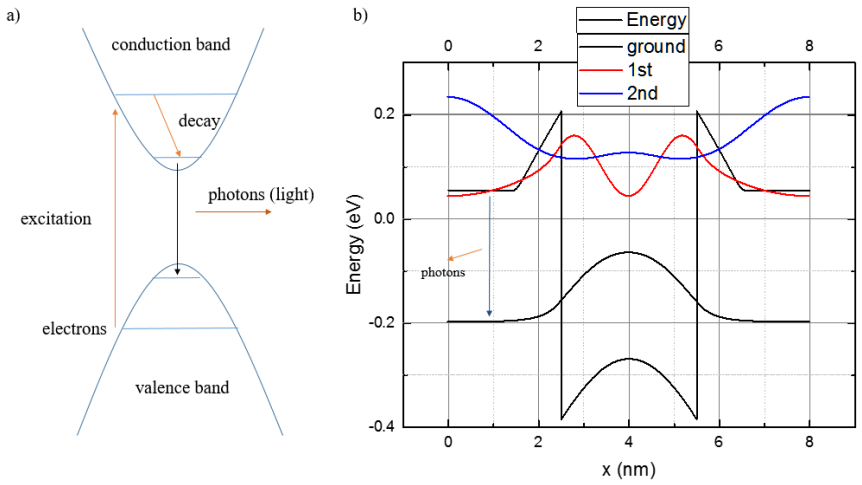

Figure 1. Interband transition (a) and intersubband transition (b). The quantum well (b) is formed by $Al_{0.22}Ga_{0.78}N/In_{0.12}Ga_{0.88}N/Al_{0.22}Ga_{0.78}N$.

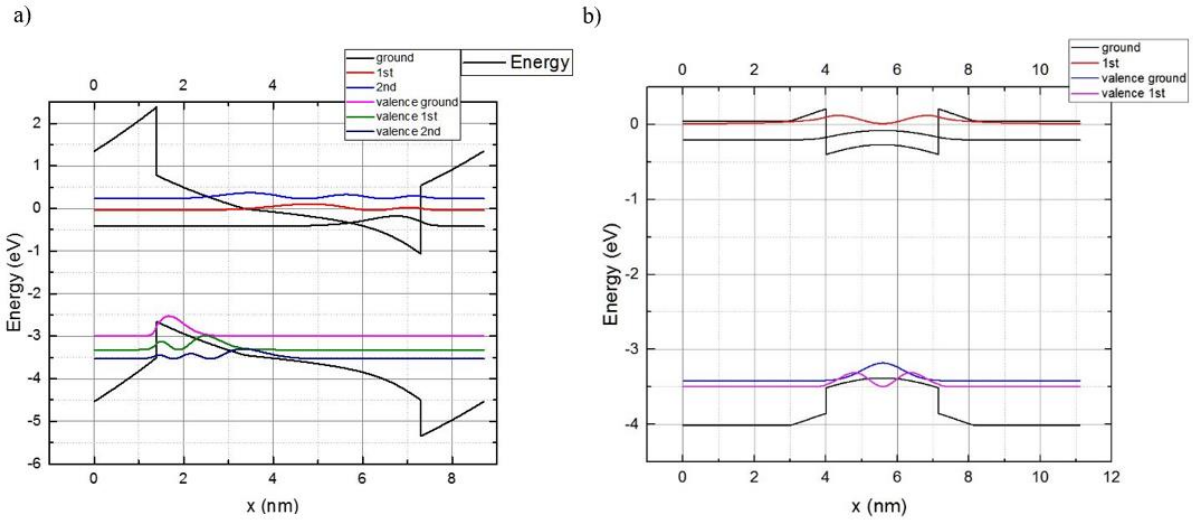

Figure 2. A tilted band structure (a) and a symmetrical band structure (b). They are formed by AlN/GaN/AlN and $Al_{0.22}Ga_{0.78}N/In_{0.12}Ga_{0.88}N/Al_{0.22}Ga_{0.78}N$, respectively.

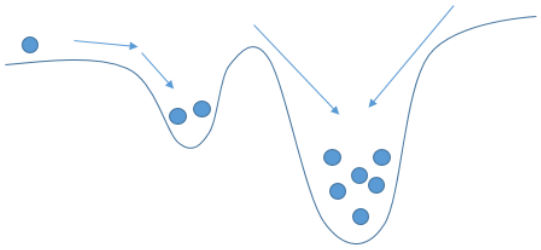

Figure 3. The bottom of conduction band is not flat due to non-uniform distribution of In. Electrons move to the potential minima and then trigger the interband transition.