氏　　　　名	片山浩二（かたやま こうじ）
学位の種類	博士（工学）
学位記番号	乙第　9号
学位授与年月日	平成１７年　３月１８日
学位授与の要件	学位規則第４条第２項該当
学位論文題目	ZnSe-based laser diodes and white light-emitting diodes grown homoepitaxially on conductive ZnSe substrates （導電性 ZnSe 基板上へホモエピタキシャル成長した ZnSe 系半導体レーザ及び白色発光ダイオードの開発）
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学位論文の内容の要旨

While many organizations have abandoned ZnSe for GaN in the race for commercialization of short wavelength light-emitters during the past decade, research in II-VI light-emitting materials is still continuing in areas where GaN-based devices have yet to be realized. This dissertation is involved with two such applications, namely the blue-green laser diode (LD) and the phosphor-free ZnSe-based white light-emitting diode(w-LED).

In the first part of this thesis work, the advantages of homoepitaxy in the development of ZnSe-based blue-green LDs are investigated. Room temperature continuous wave (CW) operations of ZnSe-based LDs grown homoepitaxially on conductive ZnSe substrates with threshold current densities as low as $176A/cm^2$ are demonstrated. The employment of a transparent ZnSe substrate leading to the low internal loss is found to be responsible for the exceptionally low threshold. However, laser lifetimes under room temperature CW operation are limited to 7.5 hours owing to the rapid degradation caused by the generation of dark line defects. Further reductions in the threading dislocation densities are needed to assess the advantages of homoepitaxy in terms of device lifetime.

In the second part of this thesis work, the development of the phosphor-free ZnSe-based w-LED is presented. The present device utilizes a phenomenon unique to ZnSe homoepitaxy, where a portion of the main greenish-blue emission from the active layer of a pn junction diode is absorbed by the conductive substrste which in turn gives off an intense broad-band yellow emission centered near 585-595nm by photoluminescence. These two emission bands combine to give an optical spectrum which appears white to the naked eye. A typical ZnSe-based w-LED exhibits a color temperature of approximately 3400K with a color rendering index (CRI) of 68. The optical power and forward voltage at a forward current of 20mA is over 8mW and 2.5V. The luminous efficacy estimated from these results is 33lm/W, which is comparable to or even higher than the incandescent lamp as well as the commercial GaN-based w-LED.

The third part of this thesis work deals with the lifetime issues of the ZnSe-based w-LED. Two major degradation mechanisms, namely the *rapid mode* due to pre-existing macroscopic defects and the *slow mode* due to point defects generated in the p-ZnMgSSe layer, are investigated. The former mechanism, which is held responsible for the degradation of LDs, is found to have a minimal effect on the lifetime properties of ZnSE-based w-LEDs owing to the lower current injection level. On the other hand, the latter mechanism, which is comprised of two separate phases, has more serious consequences as described below:

Phase I : Generation of microscoopic dark spots or DLDs, whose generation rate corresponds to the initial concentration of the N-related deep level H0 ($E_T-E_V=0.8 \pm 0.2eV$) in the p-ZnMgSSe layer, is Found to limit the device lifetime. H0 is an electrically active defect and diffuses to the active layer during current injection, where it accumulates to form the microscopic dark spots.

Phase II: Deterioration of the internal quantum efficiency, resulting from the carrier removal effect in the p-ZnMgSSe cladding layer, is found to be a dominant life-limiting effect. The cause of the carrier removal effect is belived to be due to electrons overflowing into the p-ZnMgSSe layer, which recombine non-radiatively in an recombination-enhanced defect reaction (REDR) process creating new compensating defects.

Based on these insights obtained from the degradation studies, an i-ZnMgBeSe/p-ZnMgSSe double cladding layer structure was designed and employed, resulting in a significant improvement in the room temperature lifetime from 3,000 hours to over 10,000 hours at a current density of $16.5A/cm^2$. The i-ZnMgBeSe serves as an efficient electron blocking layer, thus, suppressing the carrier removal effect in the p-ZnMgSSe.

論 文 審 査 の 結 果 の 要 旨

本研究は、ZnSe 系Ⅱ－Ⅳ族化合物半導体による青緑色レーザーダイオード(LD)、および白色発光ダイオード(白色 LED)の実用開発に関するものである。デバイス開発の基礎となる MBE 成長（分子線エピタキシャル成長）から実用水準まで素子性能を向上させた系統的な研究成果をまとめた

もので、研究の概要と主要な成果を以下に示す。

① ZnSe 結晶薄膜のホモエピタキシャル成長（ＭＢＥ成長）技術の確立：

従来の異種基板上への結晶薄膜成長の持つ欠点（特に欠陥発生）を克服する ZnSe 薄膜のホモ・エピタキシャル成長（同一基板上のエピ成長）技術を確立し、結晶内のマクロ・ミクロ欠陥の発生を制御した LD および LED 素子開発のベースを構築した。

② ZnSe-ZnMgSSe 系 SCH 構造（分離閉じこめ型 LD）・LD 素子および白色 LED 素子の肺発：

量子井戸活性層(ZnCdSe/ZnSe)を ZnMgSSe クラッド層で挟んだ SCH 構造・青緑色半導体 LD 素子および白色 LED 素子の開発を行った。青緑色 LD 素子は、同種半導体の中でも最も低い発振閾値(16A/cm^2)を達成し、ホモエピタキシャル結晶の高品質性（特に欠陥制御）を検証した。ZnSe 白色 LED 素子は、活性層からの青緑色発光とその直接励起により生じる ZnSe ホモ基板からのオレンジ発光の混色で白色を実現する、非常にユニークな全固体・白色 LED である。本研究のポイントは、最大の技術課題であった「短い素子寿命（数千時間動作）」の要因となるミクロ点欠陥（Ｎ複合欠陥）の発生・増殖を人工的に制御した新素子構造「ダブル・クラッド構造 SCH 白色 LED」の開発である。新構造白色 LED 素子は低動作電圧（＜2.5V)、高輝度(＞30lm/W)且つ長寿命動作を実証した。本研究で作製された ZnSe 白色 LED 素子は、室温・連続動作試験において１万時間以上の安定動作を示し、初めて実用応用への道を開拓した。

これらの研究成果は白色 LED 素子の実用開発に留まらず、Ⅱ－Ⅵワイドギャップ半導体・素子開発のボトルネックであった「欠陥発生・増殖の課題」を克服する新技術を世界に初めて示すものであり、博士（工学）としての価値を持つものと判定する。