Pulsed Laser Epitaxy of p-type ZnO Realizing Light Emitting Diode

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We report on a conversion of ZnO into *p*-type by nitrogen doping during laser molecular beam epitaxy (L-MBE), which enables us to fabricate blue light emitting diode based on ZnO *p*-*n* junctions. Behind the success, much effort has been paid to make non-doped ZnO as perfect as possible. We have marked records of the mobility (400cm^2/Vs@300K and >5,000cm^2/Vs@100K) and exciton radiative recombination lifetime (>2.5ns@300K), both of which surpass to the values achieved in world-best bulk single crystals. The residual electron concentration is as low as $10^{15}cm^{-3}$ with keeping such high quality properties. The use of $ScAlMgO_4$ substrate and proper buffer layer make it possible to grow such thin films in a persistent layer-by-layer growth mode in L-MBE [1].

Another trick was to incorporate nitrogen with high concentration ($10^{20}cm^{-3}$) with keeping such high crystalline quality by using "repeated temperature modulation technique" [2]. In this process, we repeated 15nm of nitrogen doped ZnO growth at 400^{o}C, rapid rump of temperature to 1000^{o}C, and additional growth of 1nm ZnO at the high temperature for making several hundreds nm thick films. The films show clear and reproducible *p*-type conduction as revealed by Hall effect with a hole concentration of 10^{16}-$10^{17}cm^{-3}$ and an activation energy of 100meV. We observed 420nm emission upon forward bias current drive for *p*-*i*-*n* junctions. The radiative recombination in the *p*-type ZnO by the electron injection into that layer seems to dominate.

As future challenges, we pursue higher hole concentration (>$10^{18}cm^{-3}$), doping of (MgZn)O into *p*-type and the use of ZnO single crystal substrates with aiming at practical devices.

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