Room temperature visible-light electroluminescence in Mn doped semiconductors

Pham Nam Hai1,2, Daiki Maruo1, Le Duc Anh1, Masaaki Tanaka1

1Department of Electrical Engineering and Information Systems, The University of Tokyo
2Department of Physical Electronics, Tokyo Institute of Technology
E-mail: pham@cryst.t.u-tokyo.ac.jp

Light emissions due to the d-d transitions of transition-metal (TM) doped in semiconductors are promising because they can occur in indirect band-gap semiconductors, where the band-gap emission is not effective. Electroluminescence (EL) due to the d-d transitions have been realized in TM-doped II-VI wide-gap semiconductors, such as ZnS:Mn, by applying a high electric field (10⁶ V/cm) directly to a ZnS:Mn crystal. Under this high electric field, electron carriers are accelerated to sufficiently high energy, such that these hot electrons can excite the Mn²⁺ atoms by impact excitations. However, EL due to the d-d transitions of TM atoms doped in more widely used semiconductors, such as GaAs and Si, has not been realized so far. Because of the high conductivity of TM-doped GaAs and Si, it is impossible to apply a high electric field directly to them in the same manner as was done to ZnS:Mn.

Here, we demonstrate visible-light EL due to the d-d transitions of TM in light-emitting diodes (LEDs) with GaAs:Mn [1] and Si:Mn [2], in the temperature range from 4 K to room temperature. We design p⁺-n junctions containing a p⁺ GaAs:Mn or Si:Mn layer, in which at a reverse bias voltage (-3 to -6 V), an intense electric field (~10⁶ V/cm) builds up in the depletion layers of the p⁺-n junctions. Holes are injected to the depletion layer by Zener tunneling from the conduction band or by diffusion of minority holes from the valence band of the n-type layer. These holes are accelerated to sufficiently high energy by the intense electric field in the depletion layer, and excite the d electrons of Mn in the p⁺ GaAs/Si:Mn layer by impact excitations when they exit the depletion layer (Fig. 1). In GaAs:Mn based LEDs, we observe visible-light (reddish-yellow) emission at $E_1 = 1.89$ eV and $E_2 = 2.16$ eV, which are exactly the same as the $4^4T_1(4G) \rightarrow 6^4A_1(6S)$ and $4^4A_2(4F) \rightarrow 4^4T_1(4G)$ transition energy of the Mn ions in ZnS [3]. In Si:Mn based LEDs, we observe visible-light emission at $E_1 = 1.75$ eV and $E_2 = 2.30$ eV. For both the GaAs:Mn and Si:Mn based LEDs, the threshold voltage for the observation of visible-light EL is -4 V, corresponding to $-(E_1+E_2)/e$. This indicates that the impact excitation is most effective for the one step excitation from the ground state $6^4A_1(6S)$ to the highest excited state $4^4A_2(4F)$, while the light emission occurs by two step transitions between $4^4A_2(4F)$, $4^4T_1(4G)$, and $6^4A_1(6S)$. Furthermore, we show digital data transmission using direct amplitude modulation of our LEDs at room temperature, up to 1 Mbps, which is limited only by the RC time constant of our LEDs.

This work is supported by Grant-in-Aids for Scientific Research including the Specially Promoted Research, and the Project for Developing Innovation Systems of MEXT.