Vacuum 137 (2017) 38–41

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Enhanced performance of quantum dots light-emitting diodes: The case of Al_2O_3 electron blocking layer

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ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form
13 November 2016
Accepted 13 December 2016
Available online 14 December 2016

Keywords:
Atomic layer deposition (ALD)
Electron blocking layer (EBL)
Aluminum oxide (Al_2O_3) thin film
Quantum dots light-emitting diodes (QLEDs)

ABSTRACT

Atomic layer deposition (ALD)-processed aluminum oxide (Al_2O_3) thin film is introduced as an electron blocking layer (EBL) for quantum dot light-emitting diodes (QLEDs). The optimized Al_2O_3-based QLED exhibits the external quantum efficiency (EQE) of 2.2% with a maximum brightness of 49,410 cd m^{-2}. The key parameters including the current efficiency (CE), power efficiency (PE), and lifetime of Al_2O_3-based QLEDs are comparable to the common QLEDs, further demonstrating that Al_2O_3 is an effective EBL for QLEDs.

1. Introduction

QLEDs have been regarded as a strong candidate for the next generation solid state lighting and displays because of their tunable wavelength across the whole visible range and narrow full-width-at-half-maximum (FWHM) [1]. Since the first demonstration two decades ago [2], some key device parameters such as the external quantum efficiency (EQE), luminance, current efficiency (CE) and lifetime of QLEDs have improved greatly as a result of the optimization of the device architecture and advancement of the fabrication techniques [3], the choices of proper materials for charge injection and transportation [4], and the structure variation of the QDs themselves [5].

However, the EQEs of QLEDs for blue, green and red devices were still relative low compared with that of the state-of-art OLEDs [6]. Such low efficiency could be attributed to a number of factors, including luminescence quenching by QD charging, luminescence quenching of QDs by plasmon modes in highly conductive electrodes, or due to imbalance in the charge carriers injected into the electron emissive layers (EMLs) of the device, leading to current leakage [7]. Among these, the carrier imbalance is one of the main factors causing the low EQE. Therefore, it is significant to balance the carrier transport rate from the electron transport layer (ETL) and hole transport layer (HTL) to the EML. Usually, the mobility of electron is much high than that of the hole due to the relative small effective mass of electron, as a result, many electrons have transport across the EML to accumulate in QDs and HTL leading to the imbalance of carriers transportation. In order to overcome the bottleneck, recently, Peng group [8] have reported that an insulating layer of PMMA was inserted between the EML and the ETL to optimize charge balance in the QLED device to preserve the superior emissive properties of the QDs to play an electron blocking layer (EBL) role. However, the PMMA layer is deposited on the top of EML by a spinning-coating method, which is difficult to control the ultrathin film thickness precisely, therefore, it is still necessary to seek an effective technique to fabricate the EBL and control its thickness accurately. In this work, the Al_2O_3 thin film was deposited on the top of EML by a thickness-precisely controlled ALD method to apply as an EBL in QLED to show obvious enhanced performance.

2. Experimental procedure

All the reagents used in the experiments were in analytic grade (purchased from Shanghai Sinopharm Chemical Reagent Co., Ltd) and used without further purification.

2.1. The preparation of Al_2O_3 thin film

The Al_2O_3 thin film was deposited on the top of EML (QDs layer)

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http://dx.doi.org/10.1016/j.vacuum.2016.12.017

in an ALD system (type: PPICOSUNR-150). Trimethylaluminum (TMA) and O_2 are utilized as precursor and oxidant to flow in pulse mode as source materials to grow Al_2O_3, and a radio frequency supply as the power source. The chamber pressure was ~0.4 Pa, where argon was applied as the carrier and purge gas at flow rate set at 20 sccm and 30 sccm, respectively, whereas the flow rate of O_2 was 15 sccm. TMA flow time is 4 s, Ar purge time is 20 s, the O_2 pulse time is 10 s, and the Ar purge time is 20 s. The deposition rate is 0.15 nm per cycle, and the thickness of obtained Al_2O_3 thin film is 3 nm after 20 cycles.

2.2. The fabrication of the QLED

The patterned ITO substrates with a sheet resistance of ~20 Ω sq^{-1} were ultrasonically cleaned subsequently with deionized water, acetone, and isopropanol for 15 min, respectively, followed by treating with ozone generated by ultraviolet light in air for 15 min. Then the prepared substrates were spinning-coated by PEDOT: PSS at a rotation speed of 3000 rpm, followed by an annealing process at 120 °C for 15 min in air. Then the substrates were transferred to a N_2-filled glove-box for spin-coating of the TFB, CdS/CdSe/ZnS QDs, and ZnO NCs layers. The TFB hole transport layer (HTL) was spin-coated at a speed of 3000 rpm for 45 s, then annealing at 150 °C for 30 min. The spin speed for QD emitter layer (15 mg ml^{-1}, toluene) and ZnO HTL (30 mg ml^{-1}, ethanol) were 2000 rpm and 3000 rpm, respectively, followed by annealing at 60 °C for 30 min. These multilayer samples were then loaded into a custom high-vacuum chamber (pressure, ~3×10^{-7} Torr) to deposit the top Al cathode (100 nm thick) patterned by an in situ shadow mask to form an active device area of 4 mm^2.

2.3. Characterization and electrical luminance performance test

The samples were characterized by atomic force microscopy

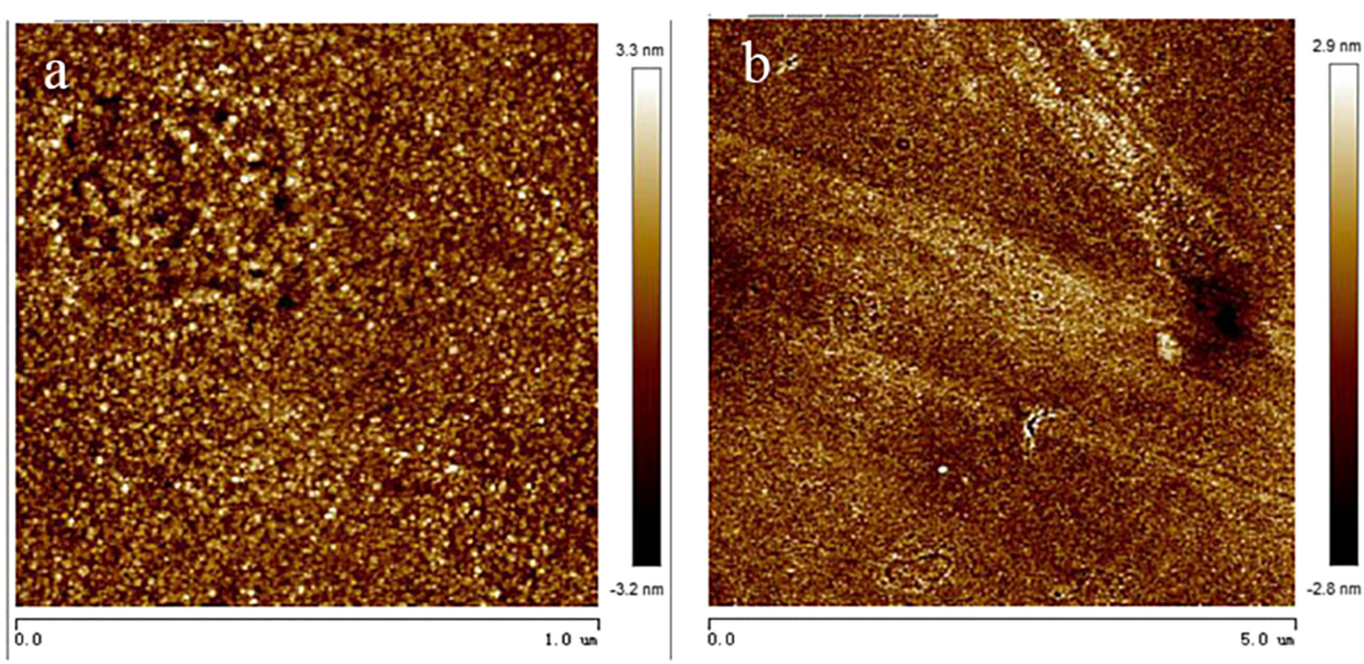

Fig. 1. Two-dimensional (2 D) AFM height images of obtained Al_2O_3 layer on ITO substrate with the scanning scale of 1 μm^2 (a) and 5 μm^2 (b).

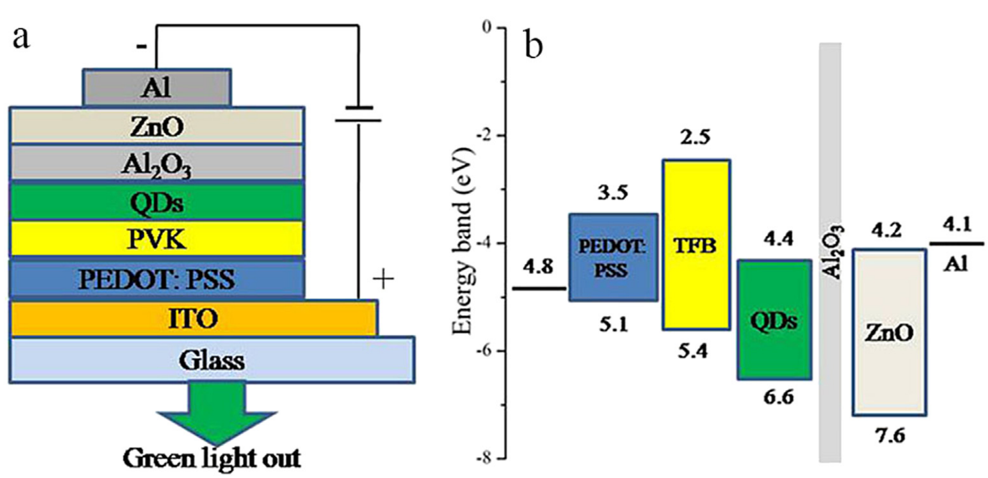

Fig. 2. Schematic diagrams of the Al_2O_3-based QLED (a), energy level alignment of the QLED (b).