ABSTRACT

Hybrid integration of CdS filters, GaN light-emitting diodes (LEDs) and disposable microfluidics can enable the creation of low-cost autonomous biophotonic chips for fluorescence detection. Sensitive fluorescence detection techniques are a significant demand in biological assays. In such applications, the optical filter performs a critical function in separating the fluorescence emission photons from the more-intense excitation light. In comparison with distributed Bragg reflectors (DBRs), which can be used to successfully filter the excitation signal, the fabrication process of thin CdS films is more straightforward and contains greater process latitude. This report demonstrates that a single CdS film of 2.4 µm can accomplish the same function as many layers of a DBR in the optical filter application of fluorescence detection.

INTRODUCTION

Laser-induced fluorescence (LIF) detection is the preferred detection technique for biochip applications because of its selectivity and high sensitivity. Though avalanche photodiodes (APDs) exhibit wavelength-selectivity, and can be integrated at the wafer and chip level [1], others have found that they require prohibitively large areas [2]. Many researchers, however, use PIN photodiodes [3-4]. Since these do not discriminate between photon signals arising from various wavelengths, separating the fluorescence emission photons selectively from the more-intense excitation light becomes of paramount importance.

Thin-film interference filters such as distributed Bragg reflectors (DBRs) have been used by various groups to filter the excitation signal [4-6]. The inherent difficulty with this approach is that the fabrication process of the DBR is expensive, time-consuming, and complicated since it requires the precise control of deposition conditions to maintain film thickness specifications for many layers. Furthermore, such filters display undesirable angular dependence due to the Bragg design constraint [4].

DESIGN AND FABRICATION

A schematic of the hybrid integration of a CdS filter, GaN blue LED, and disposable PDMS microfluidic device is described for the development of sensitive biochip-based on fluorescence detection.

Cadmium sulfide, with a bandgap of 513 nm, is a viable candidate for an optical filter in biofluidic detection applications in which the dye’s excitation is in the blue (470-490 nm) and emission in the green (510-530 nm). It is a direct bandgap semiconductor, and consequently possesses a steep absorption edge, resulting in a sharp transition between absorbed and transmitted wavelengths. This is important because some dyes (e.g., YOYO) have Stokes’ shifts as small as 17 nm [7].

In this paper, a hybrid integration of a CdS filter, GaN blue LED, and disposable PDMS microfluidic device is described for the development of sensitive biochip-based on fluorescence detection.
The process flow involves a PECVD deposition of 1500 Å of SiO₂ onto a silicon photodiode substrate [8]. A 1-3 μm CdS film is deposited onto this SiO₂ buffer using pulsed laser deposition (PLD). The SiO₂ layer serves as a buffer preventing diffusion of the deposited species into the photodiode’s active area during PLD. The GaN LED, grown on sapphire due to epitaxial growth constraints, is transferred onto the pre-fabricated silicon photodiode substrate by a pixel-to-point double transfer technique using excimer laser lift-off and Pd-In transient-liquid-phase bonding (Fig. 3). The pixel-to-point process involves three steps: (1) temporarily bonding the LED pixel to a specially designed pick-up rod with sapphire substrates facing up using Super Glue®, (2) removing the sapphire substrates using laser lift-off, and (3) permanently bonding the LED pixel to a designated area. Our previous work has demonstrated that the laser lift-off and transfer process of GaN LEDs does not degrade performance [9]. Figure 4 shows the LEDs and their electroluminescence spectra before and after transfer.

Deposition of CdS by PLD has been previously demonstrated [10]. The technique employs a solid source (0.50” in diameter, and 0.25” thick) as in evaporation or sputtering.

RESULTS AND DISCUSSION

One difficulty associated with DBR filters is angular dependence. Figure 6 displays simulations that characterize the angular dependence of the CdS and a ZnS/NaAlF DBR filter (Omega Optical) [11].
While the cutoff wavelength of the CdS film is almost independent of incident angle and thickness, the ZnS/NaAlF shows both an angular and thickness dependence. Angular dependence is not desirable, particularly if one is collecting signal from a wide range of incident angles, as is usually the case. Another drawback to DBR filters is the requirement for severe process control. In Fig. 6d, the effect of slightly varying the film thickness of just one of the compounds by a few percent is shown. Note that the cut-off wavelength of the CdS is independent of thickness variations.

Figure 7 compares the performance of the CdS and ZnS/NaAlF DBR filters. The 2.4 µm CdS film transmits $1 \times 10^{-5}$ of the incident light while the DBR transmits only $1 \times 10^{-6}$. The DBR transmits about 80% of the emission light whereas the CdS transmits only about 50%. Considering the simplicity and greater tolerance to process variations associated with CdS film deposition, it appears that a single thin CdS film is a viable alternative to a DBR. The appropriate thickness for the CdS film is currently being optimized.

Fig 5: (a) Fabrication process of disposable microfluidics and (b) SEM image of the channel.

Fig 6: Transmission as a function of both wavelength and incident angle for (a) a 2.4 µm CdS filter and (b) a 90-layer ZnS/NaAlF DBR stack. (c) The band shift as a function of incident angle is shown for three different DBR stacks. (d) The cut-off wavelength (1% transmission) is shown as a function of percent thickness variation.

Fig 7: The transmittance of a CdS and DBR filter.
Filtering with II-VI compounds such as CdS can be extended to other wavelengths by adding a third element (e.g., Se) to vary the bandgap. As shown in Fig. 8, one could potentially fabricate filters with cut-off wavelengths varying from 513 nm to 714 nm (and hence appropriate for numerous dyes) [12]. The CdS\(_x\)Se\(_{1-x}\) system is known to have total solid solubility (i.e., from 0<x<1). Also, PLD-deposited films of CdS\(_x\)Se\(_{1-x}\) compositions have demonstrated that the absorption at the bandgap is steep regardless of the value of x [13].

Laser lift-off and transfer introduce the possibility of multicolor LEDs on the same substrate. As demonstrated in this work, pixel-to-point transfer allows individual LEDs to be lifted-off a source wafer and placed at specific locations on a photodetector substrate. It is an obvious extension of this work that the LEDs need not be of the same excitation wavelength or even color. Likewise, filters deposited onto individual photodiodes need not be of the same composition, and hence could filter different wavelengths. This type of flexibility could also be explored at the wafer level, as large-area lift-off and transfer has been demonstrated [14].

CONCLUSIONS

A hybrid integration of a CdS filter, GaN blue LED, and disposable PDMS microfluidic device for the development of autonomous biophotonic chips has been described. It features normal incidence excitation, but reduces the green excitation signal by placing the photodetectors in the same plane as the excitation source. A single layer of CdS deposited by pulsed-laser deposition exhibited comparable performance to a commercial, multilayer DBR stack. The CdS filter’s performance is independent of incident angle and is relatively insensitive to thickness variation.

The CdS\(_x\)Se\(_{1-x}\) system will be explored for potentially fabricating filters with a variety of cut-off wavelengths. The possibility of multicolor LEDs on the same substrate will continue to be evaluated. Hybrid integration of CdS or CdS\(_x\)Se\(_{1-x}\) filters with GaN LEDs and disposable microfluidics can provide an effective integration paradigm for future biophotonic chip fabrication.

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REFERENCES

[8] Provided by Photonic Detectors in Simi Valley, CA.