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PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 11 (2013) 139–144

www.elsevier.com/locate/photonics

Photonic crystal nanocavities in GaAs/AlGaAs with oxidised bottom cladding

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Received 17 October 2012; received in revised form 9 December 2012; accepted 11 December 2012
Available online 20 December 2012

Abstract

We present a solution to the difficult task of removing an oxide-based hard mask from a photonic crystal fabricated in the GaAs/AlGaAs system. We use a polymer backfill technique to seal the AlGaAs layer, thereby making it inaccessible to the wet-etch solution. This allows us to use a GaAs active layer for the photonic crystal placed on an oxidised AlGaAs layer which provides mechanical and thermal support. Using this technique, we fabricated GaAs-based photonic crystal cavities and measured respectable quality factors ($Q \approx 2200$) despite the intrinsic asymmetry of the system. The technique presents a viable method for producing electrically injected photonic crystal cavities for operation on a mechanically stable and thermally conducting buffer layer.

Keywords: Photonic crystal; Cavity; Oxide; Fabrication; Hard mask; Oxidation; Backfill

1. Introduction

Photonic-crystal cavities offer the unique ability to strongly confine light within small volumes. Currently, the majority of such cavities are realised in a suspended membrane geometry to maximise the optical confinement in the vertical direction. This geometry has some key disadvantages, however, i.e., poor mechanical stability and high thermal resistance as the cavity is surrounded by air. Different solutions, such as supporting micro-posts, bonded or embedded membranes have been used to address these issues [1–3], and the corresponding fabrication methods are limited to wafer bonding [2,3] oxide backfill [4,5] or the oxidation of the underlying layer [6]. The oxidation technique is considered as the conceptually simplest method for the realisation of an electrical device, because it can be applied to a standard wafer following lithography and etching. Also, the oxidation proceeds through the etched holes, which is simple and convenient.

The etching quality of these holes is crucial for low scattering losses and high quality-factor cavities [7,8]. In order to produce the required high aspect-ratio holes in the III–V system, a hard mask is needed [9,10]. At this point, a fundamental problem arises: hard masks usually consist of oxides that are removed by a wet-etch in hydrofluoric acid-based solutions, which, also attack the AlGaAs layer needed for the bottom cladding, especially if the AlGaAs has the high aluminium content needed for subsequent oxidation. This makes the use of an oxide hard mask particularly challenging.

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1569-4410/$ – see front matter
http://dx.doi.org/10.1016/j.photonics.2012.12.002

Here, we present a way to overcome this issue by back-filling the holes with a polymer prior to the wet etch of the hard mask and we use this process to fabricate cavities on an oxidised AlGaAs cladding with a Q-factor of up to 2200, which is higher by a factor 15 than those recently realised in the similar GaInNAs material system [11].

2. Fabrication methods

As this technique is useful for thick electrical active structures, i.e., containing current transport layers and active media, we use a 420 nm thick GaAs slab that incorporates n-type and p-type layers (for an eventual electrical injection) as well as 5 Dot-in-a-Well (DWELL) InAs active layers. This high number of dot layers has been chosen for potential high gain applications. In this context, high gain applications produce high optical output powers for strong electrical pumping conditions. This means that he generated heat needs to be dissipated efficiently, especially at room temperature. As shown in Fig. 1(a), this slab is located on top of a 500 nm thick AlGaAs layer, which will be oxidised subsequently, forming the bottom cladding. From the optical perspective, a thicker AlGaAs layer would be desirable, but increasing the thickness would also increase the risk of delamination, as the layer contracts by approximately 7% [12] during oxidation. The thicker the AlGaAs layer, the larger the absolute shrinkage, which increases the stress and hence the risk of delamination.

The first step of the fabrication procedure is to thermally evaporate a 100 nm thick layer of TiO_x as the hard mask on top of the epitaxial stack, as shown in Fig. 1(a). TiO_x is not typically used as a hard mask in photonic crystal fabrication; we use it for its ease of deposition and a high etch resistance. Next, the pattern is defined by exposing a layer of electron-beam resist (ZEP-520A) with a 30 kV Zeiss Gemini 1530/Raith Elphy electron-beam writer. Following development, the pattern is transferred into the hard mask in a parallel plate reactive-ion-etcher (RIE), with a 1:1 balanced SF_6:CHF_3 chemistry. The remaining soft mask is stripped off, and the sample is transferred into a chemically assisted ion-beam-etching (CAIBE) system for the pattern transfer from the hard mask into the III–V material stack. We use an Argon ion-beam at 500 V in combination with a chlorine fed at 80 °C to produce the structures shown in Figs. 1(c) and 2(a). At this point, some of the hard mask remains on top of the structure which prevents the formation of an electrical contact to the structure. The obvious solution would be to remove the hard mask in an additional dry-etching step, but we noticed that such a step introduces additional roughness and lattice damage that impairs the performance of the device. We hence developed a backfill technique that allows us to remove the hard mask via a wet-etch. The basic idea behind is to block of the photonic crystal holes with a polymer that can be easily dissolved afterwards. The difficult part of this process is to backfill the holes, leaving only the surface exposed to the wet etch. In order to achieve this, we used a positive resist, i.e., Shipley S1805, which can be exposed and developed from the top until the surface is exposed.

Prior to spinning the resist, we dip the sample in a 30% NH_4OH solution for 30 s to remove any native oxide that has built up at the hole sidewalls. We then apply S1805 to the sample and place it in a desiccator

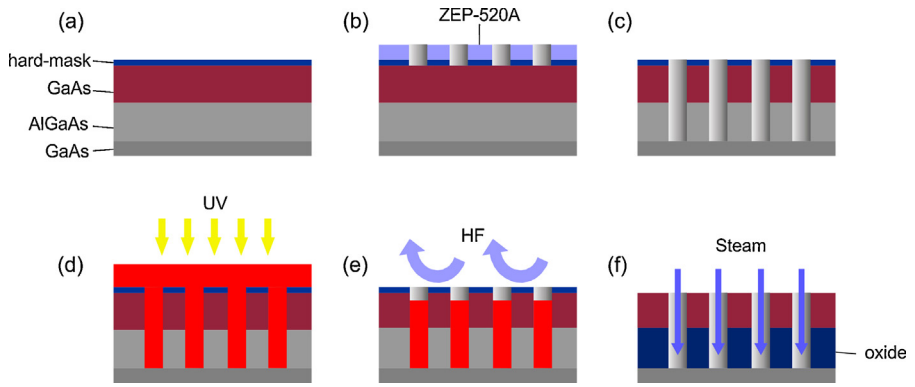

Fig. 1. Cross-sections of the structure as it evolves through the fabrication process. (a) Hard mask on top of the GaAs/AlGaAs/GaAs stack. (b) Pattern transfer from the ZEP-520A soft mask into the hard mask via RIE. (c) Pattern transfer through the hard mask into the stack via CAIBE. (d) Resist (red) backfill with successive UV exposure/resist development steps. (e) AlGaAs protection by the backfilled resist and hard mask removal with HF. (f) AlGaAs is transformed into oxide by wet steam-oxidation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)