Impact of Diffusion Mask Strain on Impurity-Induced Disordered VCSELs Designed for Single-Fundamental-Mode Operation

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The strain of diffusion masks utilized for impurity-induced disordering is demonstrated to control the curvature of the diffusion front, and therefore disordering front, of the disordered distributed Bragg reflector (DBR) aperture. As a result, the disordered apertures formed under strain conditions varying from compressive to tensile are shown to significantly impact the electro-optical performance and spectral characteristics of impurity-induced disordered (IID) VCSELs designed for single-fundamental-mode operation. An investigation and analysis of the electro-optical performance and spectral characteristics of IID-VCSELs as a result of varying diffusion mask strain is presented.

INTRODUCTION

The emergence of optical depth sensing enabled by vertical-cavity surface-emitting laser (VCSEL) arrays in consumer handheld devices has ushered in a resurgence of VCSEL research and development. Optical depth sensing techniques such as structured light for facial recognition and Time-of-Flight (ToF) Light-Detection and Ranging (LiDAR) for autonomous driving has motivated the need for improved optical beam quality, higher output powers, and greater power efficiencies in VCSEL devices.

Since its discovery by Laidig and Holonyak *et al.* [1], Impurity-Induced Disordering (IID) has been demonstrated to improve the electrical and optical characteristics of high-performance laser diodes. Disordering has been shown to modify the index of refraction, bandgap, optical reflectivity, and electrical conductivity of $Al_xGa_{1-x}As$ superlattice pairs [2,3]. Through the process of low-temperature zinc diffusion in addition to dielectric masking, IID provides a low-cost, wafer-scale process for spatially modifying the epitaxial structure after growth. Recently, the IID process has been utilized to improve the performance characteristics of high-performance VCSELs. Enhancements such as faster modulation speeds [4], lower differential resistance [5], and significantly greater single-mode output power [6] have all been demonstrated through leveraging disordered apertures.

However, previously reported works employing disordered apertures to achieve single-mode operation in VCSELs have been limited by the inability to control the diffusion front profile of the disordering aperture. As a result, the authors demonstrated the capability to control the curvature of the diffusion front, and therefore disordering front, in IID

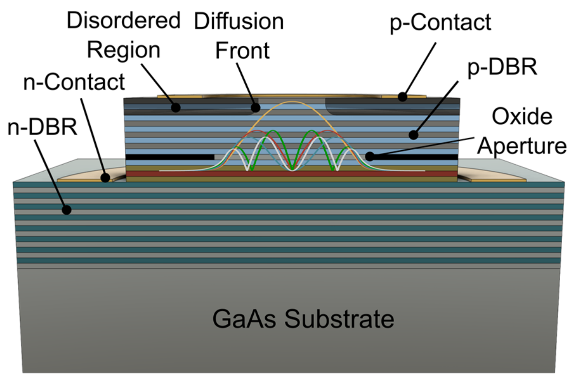

Fig. 1 Cross-sectional illustration of the IID VCSEL

VCSELs [7]. Using highly tensile-strained diffusion masks during the disordering process, high-power single-mode operation in excess of 10 mW has been achieved in IID VCSELs [8].

While tensile-strained diffusion masks have been used to demonstrate higher single-mode output powers in disordered VCSELs, devices from unstrained and compressive strained diffusion masks have yet to be investigated. This work compares the electro-optical performance as well as spectral characteristics of IID VCSELs utilizing various diffusion mask strains to form disordered apertures with different diffusion front profiles to achieve single-fundamental-mode operation in 850 nm $Al_xGa_{1-x}As$ VCSELs.

STRAIN-CONTROLLED DISORDER-DEFINED APERTURES

Surface-deposited Plasma-Enhanced Chemical Vapor Deposition (PECVD) silicon nitride (SiN_x) films are used as strained diffusion masks for the disordering process. The 50 nm thick SiN_x diffusion masks are deposited with 20 sccm SiH_4, 45 sccm NH_3, 1960 sccm, N_2, 950 mT pressure and 40 W of plasma power utilizing a dual-frequency sourced Oxford PlasmaPro 100. The strain of the diffusion masks is modified by alternating between the low-frequency (380 kHz) and high-frequency (13.56 MHz) RF generators during the deposition process. The film stress of the SiN_x diffusion masks is measured by depositing 50 nm SiNx films on 100 mm silicon wafers. Through measuring the wafer bow before and after the deposition using a Dektak XT stylus profilometer, the film stress can be determined using Stoney's Equation [9]. By exclusively using the high-frequency or low-frequency source for the deposition process, tensile- (+639 MPa) and compressive-strained SiN_x (-579 MPa) films can be formed respectively. Through equally alternating between the high-frequency and low-frequency RF sources in 20 second intervals, a mixed-frequency film is deposited that yields a nearly unstrained (-8.5 MPa) film.

All three strained films are utilized as diffusion masks to form disorder-defined apertures in impurity-induced disordered VCSELs designed for single-fundamental-mode operation. As reported in prior work [6-8], the curvature of the diffusion front of the disordered aperture is modified by the diffusion mask strain. As a consequence, these films with distinctly different diffusion mask strains are expected to yield unique diffusion front profiles that affect the electro-optic and spectral characteristics of the IID VCSELs fabricated in this work.

DEVICE DESIGN AND FABRICATION

A cross-sectional schematic of the IID VCSEL device design is shown in Fig. 1. As shown, the disordered region is defined in the shape of an aperture where the center is non-disordered. As a result, the fundamental-mode that resonates in the center of the device is not affected whereas the higher-order modes that resonate near the edges of the device experience significantly lower optical reflectivity and increased absorption losses from the disordered region [4-8]. For optimal higher-order mode suppression, the disordered aperture size is adjusted to accommodate the spatial transverse-mode profiles of different oxide-apertures. The devices fabricated in this work are designed to have a 10 µm oxide-aperture with a strained-diffusion mask size of 5.2 µm, 7.6 µm, and 7.6 µm for the tensile-strained, unstrained, and compressive-strained diffusion masks respectively. It is noted that the disordered aperture size is commonly smaller than the diffusion mask size due to isotropic nature of diffusion, and therefore disordering. The extent of lateral disordering underneath the diffusion mask is found to affect the optical and spectral characteristics of the device, an analysis of which is presented in the Device Characterization section below.

The epitaxial structure in this work utilizes a MOCVD-grown VCSEL wafer designed for 850 nm wavelength emission that is described in detail elsewhere [8]. The fabrication process begins with depositing a 50 nm thick PECVD SiN_x film utilized as a diffusion mask. Through utilizing different RF plasma generating frequencies, the strain of the PECVD deposited SiNx is significantly modified as described in the previous section. Using this technique, tensile-strained, unstrained and compressive-strained diffusion masks were deposited on separate samples. The diffusion masks are then patterned into pillars that protect the center of the device from the disordering process using photolithography and freon-based ICP-RIE dry etching. The samples are then loaded into a quartz-ampoule with a solid zinc arsenide source and sealed under vacuum (< 5 x 10^{-6} Torr). Afterwards, the ampoules are loaded into a furnace for 20 minutes at 650°C to diffuse Zn and induce the disordering of the DBR to a depth of approximately 1 µm. Once the disordering process is complete,

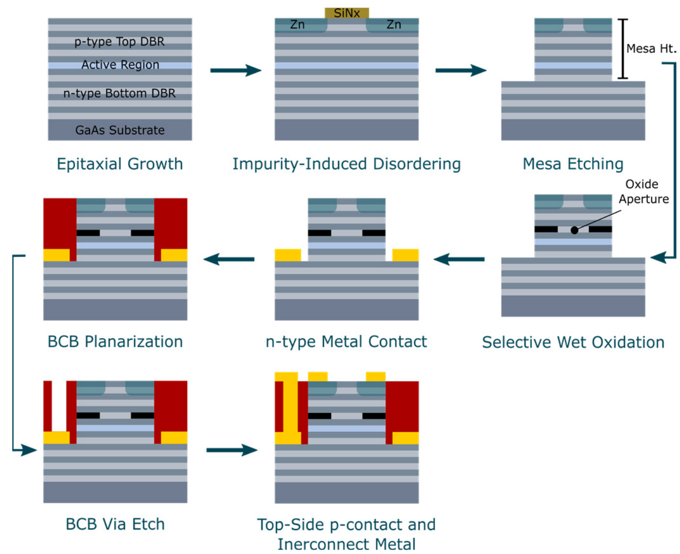

Fig. 2 Fabrication process flow of IID VCSEL

the strained diffusion masks are removed such that strain itself does not impact the electro-optic performance of the VCSEL beyond modifying the curvature of the disordering front. The remainder of the process follows a standard oxide-VCSEL fabrication flow.

First, the VCSEL mesas are defined using $BCl_3/Cl_2/Ar$ gasses in an ICP-RIE dry etch system. The etch is terminated precisely after etching 2 pairs into the bottom n-DBR using an in-situ laser-interferometer that monitors DBR reflectance. This etch exposes the high-aluminum content AlGaAs oxidation layer for wet oxidation as well as to electrically isolate the active region. The VCSELs are then immediately loaded into a wet furnace to selectively form 10 µm oxide-apertures. Next, AuGe/Ni/Au is deposited on the exposed n-type material to form an electrical contact using e-beam evaporation and photolithographic lift-off processes. The samples are annealed at 380°C to from Ohmic contacts. The samples are then planarized with Dow BCB 3022-46. A contact via is formed through the BCB using fluorine-based RIE dry etching. Subsequently, the p-contact (Ti/Pt/Au) and interconnect layer (Ti/Au) are deposited and annealed. It is noted that all devices shown in this work follow the same process flow with the exception of the variation in diffusion mask strain used during the disordering process step.

DEVICE CHARACTERIZATION

Electro-optic and single-mode performance of fabricated devices is tested under continuous-wave room-temperature operation. The electro-optic performance is characterized using light-current-voltage (L-I-V) measurements whereas the single-mode performance is determined by examining the optical spectrum. The I-V of the devices are measured using an HP4155B semiconductor parameter analyzer whereas the light output power (L) of these devices is collected with a Newport 818-UV broad area silicon detector with an attached OD3 filter and plano-convex lens to prevent detector saturation as well as to optimize collection efficiency of the detector. The optical spectra of the devices are measured by collecting the optical emission of the IID VCSELs using a ball-lensed optical fiber which is coupled into multi-mode patch cable. The multi-mode patch cable is then connected to the input of an HP70951B optical spectrum analyzer. Single-mode operation in this work is defined by a side-mode suppression-ratio (SMSR) of greater than 30 dB measured from the peak of the fundamental-mode to the peak of the most prominent higher-order mode, as is typically defined in the field [4-8]. In Fig. 3, the light-current-voltage (LIV) characteristics of the 10 µm oxide-aperture IID VCSEL using the tensile, unstrained, and compressive diffusion mask during the disordering process is shown. The corresponding optical spectra of these devices operating at their respective peak operating output powers are shown in Fig. 4.

As shown in Fig. 3, the IID VCSEL that utilizes a tensile-strained diffusion mask emits with a rather high output power compared to the other strains. This is due to the reduced lateral encroachment of the diffusion front onto the fundamental-mode of the device as demonstrated in prior work [6-8]. However, in this instance, the disordered aperture size is too large to fully suppress all of the higher-order modes despite being smaller than the unstrained and compressively strained diffusion mask design sizes. As illustrated in Fig. 4, the IID VCSEL that utilizes the tensile-strained diffusion mask shows few-moded operation where the first higher-order mode also lases. For the IID VCSEL that utilizes an unstrained diffusion mask, the optical output power is found to be lower than the device having a tensile-strained diffusion mask. However, the device is found to operate in single-fundamental-mode operation with a peak single-mode output power of 5.86 mW and a SMSR of 34.43 dB. Lastly, for the IID VCSEL that utilizes a compressively strained diffusion mask emits the lowest optical output power (5.54 mW) among the three devices, however, operates with the highest SMSR (35.64 dB) out of all the devices measured. As the diffusion mask strain becomes more compressively strained, the diffusion front of the disordering aperture begins to change from preferentially disordering in the vertical direction to preferentially disordering in the lateral direction [6-8]. As the compressive-strained diffusion mask yields the greatest lateral extent of the disordering aperture, the higher-order modes are more sufficiently suppressed which leads to the higher SMSR observed in the optical spectral characteristics of Fig. 4. However, this also leads to increased lateral encroachment of the disordered aperture onto the fundamental mode. This results in lower optical output power of IID VCSELs using more compressive-strained diffusion masks, but also increased laser threshold current as observed in Fig. 3 for the IID VCSEL using the compressive-strained diffusion mask.

The three diffusion mask strains that form distinctly different diffusion front profiles present the opportunity to form IID apertures tailored for desired performance characteristics. While using a tensile-strained diffusion mask results in a device shown to operate in few-moded operation,

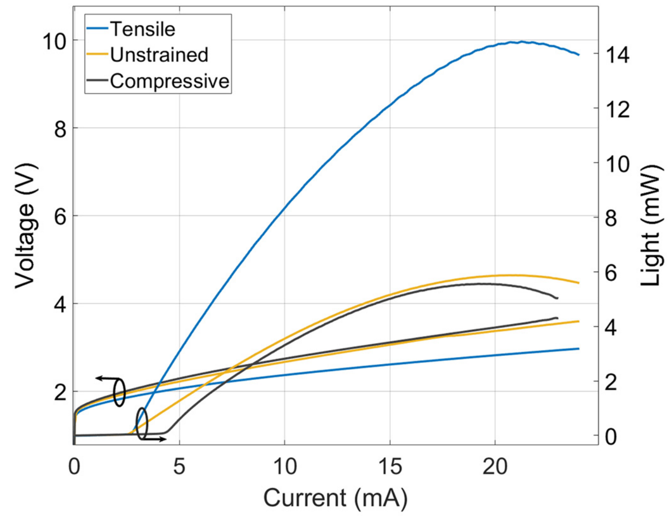

Fig. 3 Light-current-voltage (LIV) characteristics of 10 µm oxide-aperture IID VCSEL using various diffusion mask strains.

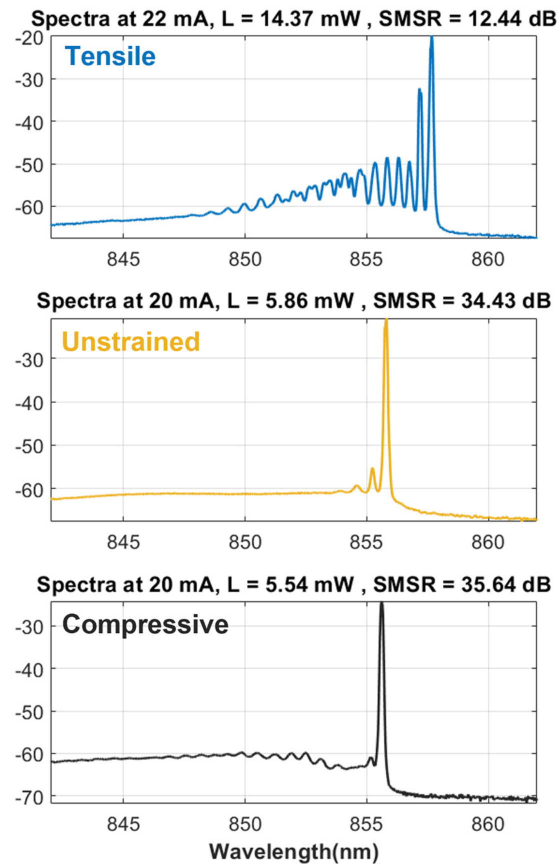

Fig. 4 Optical spectra at peak optical output power of 10 µm oxide-aperture IID VCSEL using various diffusion mask strains.

the output power is nearly twice the amount of the unstrained and compressive-strained diffusion mask devices. For high-power single-mode operation, the IID aperture size can be slightly reduced to sufficiently suppress all of the higher-order modes and thus leading to high-power single-mode output. This has been demonstrated to achieve single-fundamental-mode output power in excess of 10 mW [8]. On the other hand, using the compressively strained diffusion mask results in a device that operates with high SMSR to the fundamental mode. For applications sensitive to maintain single-fundamental-mode output, the compressive-strained diffusion mask can be utilized to achieve stable single-fundamental-mode performance in IID VCSELs.

CONCLUSIONS

The impact of modifying the shape of disordered apertures as a result of varying diffusion mask strain on IID VCSEL devices designed for single-fundamental-mode operation is presented. The compressively strained diffusion mask results in devices with stable single-mode operation, but lower output power whereas tensile strain in the mask results in greater output power, but a greater risk of being unable to suppress the higher-order modes. The unstrained diffusion mask results in devices that are a balance between single-mode performance as well as greater optical output power shown using the tensile and compressive strained diffusion masks respectively. This analysis presents the importance of controlling diffusion mask strain for the disordering processes, but also presents the opportunity of tailored IID apertures optimized for single-fundamental-mode performance.

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