Impact of Strain in Diffusion Masks for Impurity-Induced Disordered VCSELs Designed for Single-Fundamental-Mode Operation

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The strain of diffusion masks utilized during the disordering process is demonstrated to modify the curvature of the disordering aperture. As a result, the various disordering apertures formed are shown to significantly impact the electro-optical performance and spectral characteristics of impurity-induced disordered 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 strains is presented.

INTRODUCTION

The emergence of optical depth sensing enabled by vertical-cavity surface-emitting laser (VCSEL) arrays in consumer handheld devices has ushered 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 qualities, 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 diode designs. 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, disordering presents a low-cost, wafer-scale process of spatially modifying the epitaxial design of the laser structure. Recently, disordering has been utilized to improve the performance characteristics of high-performance VCSELs for emerging applications. 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 disordering apertures. However, during the disordering process, any lattice mismatch between the diffusion mask and cap layer of the epitaxial structure induces biaxial strain. As a result, the diffusion mask strain has been shown to greatly modify the diffusion front of the disordering aperture [7]. This work investigates the performance impact of various diffusion mask strains on disordered VCSELs designed for single-fundamental-mode operation.

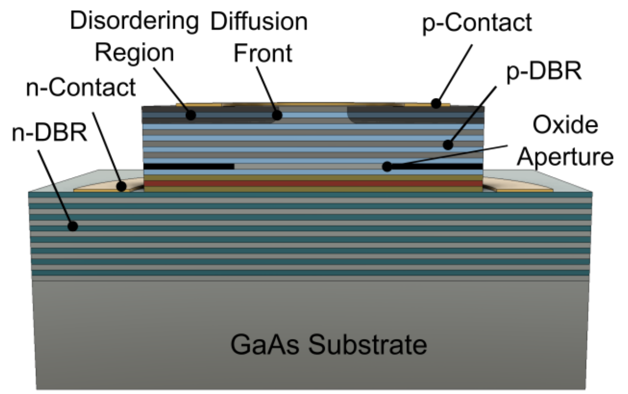

Fig. 1 Cross-sectional illustration of IID VCSEL

DEVICE DESIGN AND FABRICATION

The epitaxial structure in this work utilizes an MOCVD-grown VCSEL wafer designed for 850 nm wavelength emission that is described in detail elsewhere [6]. A cross-sectional schematic of the device design is shown in Fig. 1. The fabrication process begins with strained PECVD-grown silicon nitride (SiN_x) being deposited with 20 sccm SiH_4, 45 sccm NH_3, 1960 sccm N_2, 950 mT pressure, and 40 W of radio-frequency (RF) plasma power. Through utilizing different RF plasma generating frequencies, the composition of the PECVD deposited SiNx is significantly modified. As a result, low-frequency and high-frequency deposited silicon nitride were measured to yield compressive (-579 MPa) and tensile (+639 MPa) respectively. Through periodically alternating equally between the low- and high-frequency RF sources during the deposition process, a mixed-frequency film was deposited and measured to yield a nearly un-strained film (-8.5 MPa). All three of these films were utilized as diffusion masks for the disordering process in the fabrication of single-mode VCSELs via impurity-induced disordering. After the disordering process is complete, the strained diffusion masks were removed such that the strain does not impact the electrical and optical performance of the VCSEL beyond modifying the disordering aperture. The remainder of the process follows a standard oxide-aperture VCSEL process. The mesas are etched using chlorine-based ICP-RIE dry etching followed immediately by a wet oxidation process to selectively form 9 µm oxide apertures. Afterwards, the n-

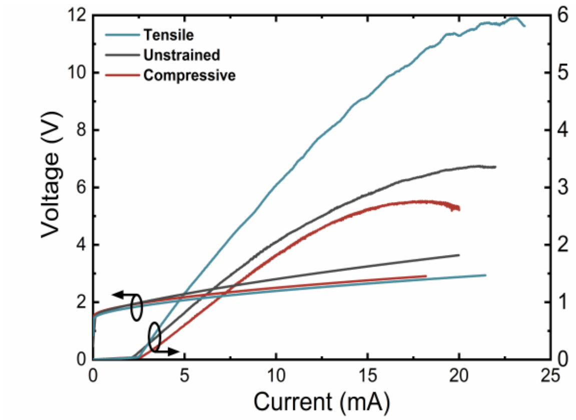

Fig. 2 Light-Current-Voltage (LIV) characteristics of IID VCSELs designed for single-mode operation

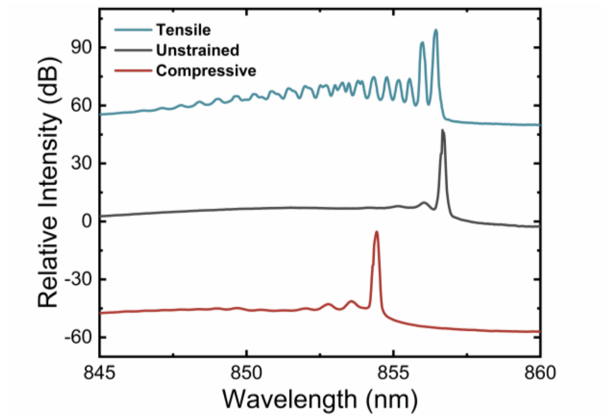

Fig. 3 Measured spectra of IID VCSELs exhibiting modal characteristics of the fabricated devices

contact (AuGe/Ni/Au) contact is deposited via e-beam evaporation and annealed to form Ohmic contacts. The devices are then planarized with BCB to provide electrical isolation. A contact via is formed through the BCB using fluorine-based RIE dry etching. The p-contact (Ti/Pt/Au) and interconnect layer (Ti/Au) are deposited and annealed subsequently. It is noted that all devices shown in this work follow the same process flow with the exception of the variating diffusion mask strain applied for the disordering process.

Device Characterization

The devices were characterized for their electro-optic performance and spectral characteristics via light-current-voltage (L-I-V) and optical spectra measurements. As shown in Fig. 2, the varying diffusion mask strains have a minor impact on the electrical performance of IID VCSELs. However, there is an evident increase in optical output powers with the compressively strained disordering aperture device emitting the lowest output power and the tensiley strained disordering aperture devices emitting the highest output power respectively. This is explained by the lateral extent of the compressively strained disordering aperture undesirably suppressing the fundamental mode [7]. As the tensiley strained disordering aperture oppositely results in a reduction in the diffusion front in the lateral direction, the higher-order modes are not sufficiently suppressed. This leads to greater output power from the device, but largely multi-mode operation as shown in Fig. 3.

Conclusions

The impact of modified disordering apertures as a result of varying diffusion mask strains on IID VCSEL devices designed for single-mode operation is presented. The compressive strain results in stable single-mode operation, but lower output power whereas tensile strain results in greater output power, but a greater risk of being unable to suppress the higher-order modes. This analysis presents the importance of monitoring diffusion mask strain in disordering processes, but also presents the opportunity of tailored disordering apertures optimized for single-mode performance.

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