Yield Improvement in Fabrication of Edge Emitting Transistor Lasers by Optimized BCB Planarization

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Abstract

An analysis into the low yield of the Transistor Laser process is performed and it is determined that the BCB planarizing polymer's spin non-uniformity is the primary cause of the failures observed. The process is modified to mitigate this effect and steps are outlined to further refine process control monitors in new layouts. The revised process is used to fabricate transistor lasers exhibiting > 14Ghz f_{-3db} optical bandwidth at 15ºC.

INTRODUCTION

The base current of the transistor supports recombination and can be used, by inserting a quantum well in the base region to trade off electrical gain for optical generation, to transform the transistor (provided a high Q cavity for stimulated emission) into a laser. Thus the device acts as both an HBT (forward biased) and a semiconductor laser [1]. The quantum well recombination competes with transport through the base region to limit the average lifetime of the minority carriers (electrons) in the base to the order of ~ 30ps [2]. The quantum well transistor laser is a novel three-port opto-electronic device that is capable of high-speed, resonance-free optical RF response [3]. In this work we discuss the failure mode of the previous generation process, the identification of the critical issue causing yield loss and the solution along with yield and device results.

EPITAXIAL STRUCTURE AND FABRICATION PROCESS

The epitaxial structure of the TL starts with a heavily doped n-type 5000Å GaAs buffer grown on SI-GaAs. Next a 5000Å n-type $Al_{0.95}Ga_{0.05}As$ layer that functions as both the sub-collector and as the laser lower cladding. The collector contact is a 200Å heavily-doped n-type GaAs layer. A 120Å $In_{0.49}Ga_{0.51}P$ etch stop layer is included for facilitating fabrication followed by a 600Å lightly-doped GaAs collector. A 1000Å heavily-doped p-type AlGaAs / InGaAs / GaAs layer serves as the base and includes one 120Å undoped InGaAs quantum well designed for 980nm emission. The emitter is a lightly-doped n-type 250Å $In_{0.49}Ga_{0.51}P$ layer followed by 4000Å of n-type oxidizable $Al_{0.95\text{-}0.99}Ga_{0.05\text{-}0.01}As$ upper cladding which serves (via lateral oxidation) to confine the current injection and laser aperture. The emitter contact layer consists of 1000Å heavily-doped n-type GaAs. Device fabrication of the HBTL consists of 9 photolithographic steps. Wet etching is used for all mesas and isolation. Base and collector contacts are evaporated prior to BCB planarization which is followed by etchback to expose the emitter and deposit emitter contacts. Next, post interconnection of the base metal to the contact pads is performed followed by a final polyimide via interconnection to realize the common emitter heterojunction bipolar transistor laser (HBTL) structure. The wafer is lapped to a thickness of 25µm, polished and cleaved into bars which are mounted to indium-coated copper heatsinks.

FAILURE MODE

Majority of device failures are characterized by low BE current in the Gummel measurement and absence of lasing as shown in Figure 1.

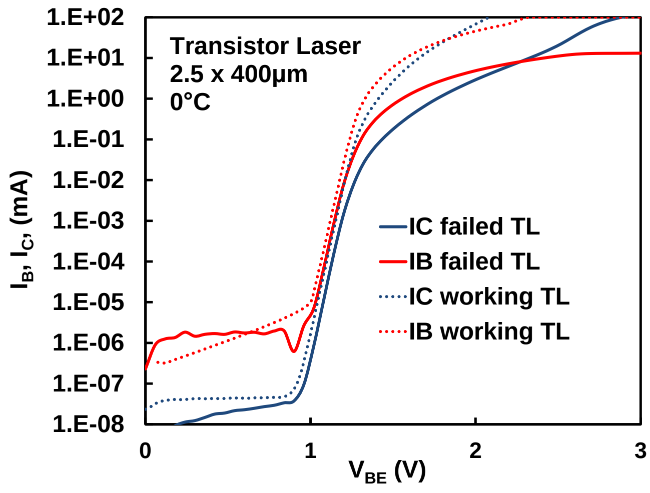

Figure 1. Gummel measurement of a failed TL (solid) compared to that of a working device (dots) showing an almost 100x increase in EB resistance. The devices measured were 400µm long and had emitter width 4µm (after etching and oxidation 2.5µm).

The process control monitor (PCM) analysis shows Base and Emitter ohmic contact resistances to be within specifications via a TLM measurement. Via and post chains show the resistances of the corresponding structures to be within specifications. The failure is repeatable for the process and even the etchback PCMs on the layout are incapable of identifying its cause.

FIB Cross Sectioning and Analysis

FIB cross sectioning reveals a discontinuity in the Emitter Metal overlap which is responsible for the failure. BCB over-etch coupled with the re-entrant etch profile of the emitter cap causes this (shown in Figure 2) and results in the B-E open failure mode. The metal discontinuity is not rectified by subsequent Metal 2 deposition and the device is seen to fail.

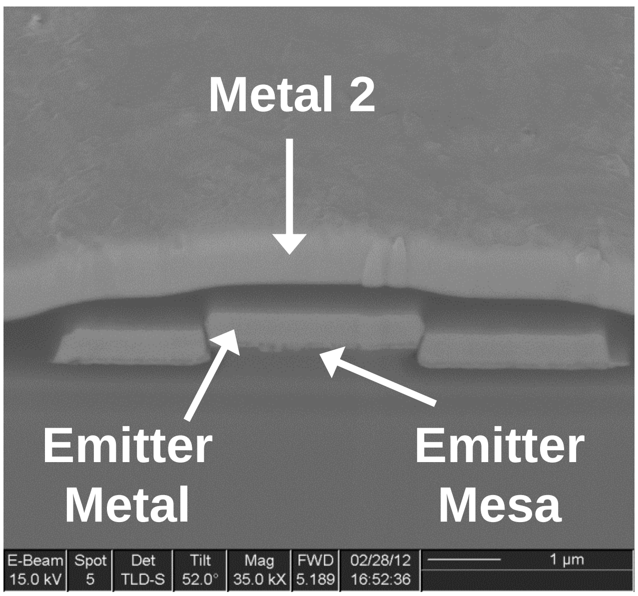

Figure 2. FIB cross-section of failed device showing discontinuity in Emitter Metal overlap due to BCB overetch.

The transistor laser is a high topography device, with almost 2µm from the top of the emitter mesa / base metal to the bottom of the isolation trench. The BCB is required to planarize this to less than 2000Å in order to acceptably expose the emitter cap layer without over-etching and damaging the base surface. FIB and SEM analysis reveal excessive non-uniformity in BCB spin-profile due to high topography, uneven feature density over device and PCM areas (Figure 3) and thin BCB. BCB 46 which is used for the process is spun on at 4000 rpm which is expected to give a 2.63µm spin height. The TL process mask consists of lasers of varying lengths; 200µm, 300µm, and 400µm, amongst a variety of large area DC test devices and PCMs. The density of features on the mask is highly uneven, and is shown in the Figure 3. It is noticed during the etchback that the emitter

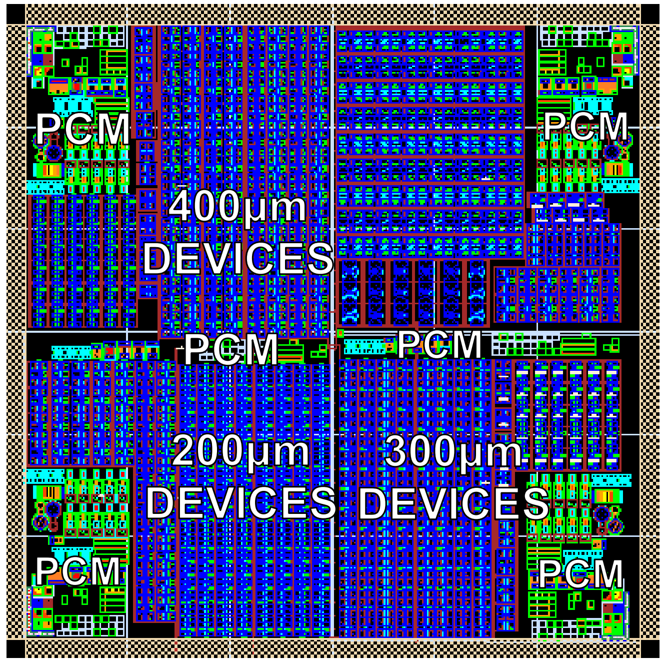

Figure 3. TL mask layout showing all processed layers to illustrate the variation of feature density across lasers of different lengths and PCM regions on the wafer. PCM regions are sparse and different sized devices have varying feature density due to pad size and pitch.

mesas for different size lasers are exposed at different times. This means a variation exists in the BCB thickness over the area of the wafer. It has been observed earlier [4] that BCB spin height is highly dependent on feature density. The work suggests the use of dummy features or algorithms to balance feature density. This also lends credence to the hypothesis that our etchback PCM design is flawed and does not represent the device accurately nor yield any worthwhile information. However, in order to determine the viability of BCB uniformity in solving the problem in a timely fashion an experiment was designed to test the effect of BCB thickness and cure on the spin profile. BCB-57 is a higher viscosity variant and is spun on with the same speed and cured in N_2 ambient at 250ºC for 8 minutes. The final thickness is measured to be over 6µm and optimal etch rate in a CF_4/O_2 plasma in an RIE is determined.

Solution and Results

BCB-57 with its spin height of 6.2µm offers much improved planarization. The PCM and device regions have different BCB spin heights; however, the variation between devices is greatly reduced allowing much tighter control over the height of the etched-back mesa. Figure 4 Shows the FIB cross section of a functioning device with excellent connection between the emitter metal and mesa. Yield is improved from ~ 10% to ~ 85% which allows for a stable baseline process to provide a test bed for future experiments.

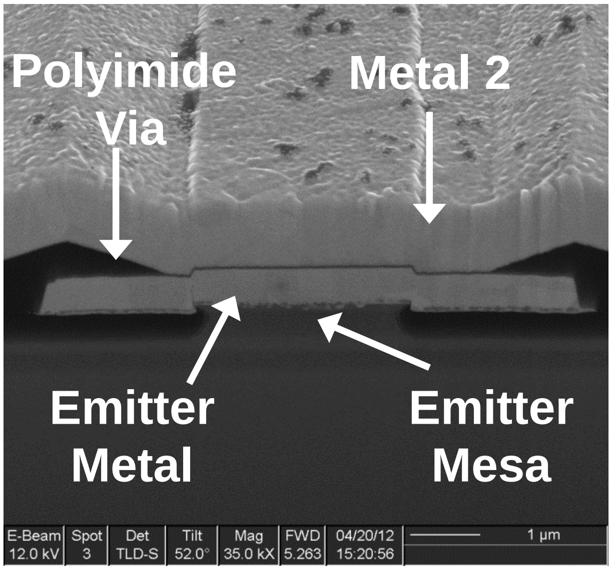

Figure 4: FIB cross-section of a functioning device fabricated using the revised process showing excellent continuity of Emitter Metal, sloping Poly-Imide vias and Metal - 2 to Emitter Metal interconnection.

The devices fabricated using this process have shown good performance and yielded transistor lasers with 14.5 GHz 3dB optical modulation bandwidth at 15°C. The frequency response of the device is shown in Figure 5. The devices have also exhibited 20Gb/s open-eye transmission from 15°C to 25°C [5].

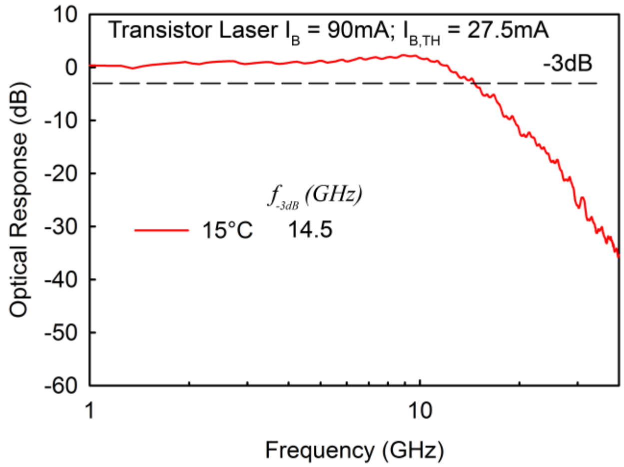

Figure 5: Measured S_{31} optical response (smoothed) of the transistor laser fabricated with the improced process showing a modulation bandwidth of 14.5 GHz at 15°C.

Conclusions

BCB spin non-uniformity is identified as the cause for catastrophic yield loss in the Transistor Laser process. Poor PCM design is to blame for the failure of the structures in identifying the problem. It is rectified by the use of thicker BCB and layout improvements are suggested for the future in order to fabricate useful PCMs. The devices fabricated by the new process show good performance and have demonstrated 20Gb/s room temperature operation.

Acknowledgements

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Acronyms

HBT: Heterojunction Bipolar Transistor
BCB: Benzocyclobutene
PCM: Process Control Monitor
TL: Transistor Laser
FIB: Focused Ion Beam
SEM: Scanning Electron Microscope