Monolithically-Integrated Quantum Dot Optical Power Monitor

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***Abstract*—A monolithically-integrated quantum dot optical power monitor is presented. The device is a laser diode whereby a fraction of the laser emission is coupled into a photodiode section via a multi-mode interferometer. The resulting photocurrent is used to assess the applicability of photodiode designs.**

***Keywords*—Monolithic Integration, Quantum Dot, Photodiode, Laser Diode, Power Monitor**

I. Introduction

There have been considerable advancements in the monolithic integration of III-V quantum dot (QD) lasers on Si which is promising for cost- and power-efficient photonic integrated circuits (PICs) [1], [2], [3]. The advantages of QDs as laser gain media include low threshold current densities, wide gain spectra and operating temperature ranges, and tolerance to lattice defects associated with III-V growth on Si. Despite the progress in monolithic laser integration, the relative maturity in the monolithic integration of III-V photodiodes (PDs) on Si lags behind. More often, Ge-based photodetectors are preferred due to their compatibility with silicon CMOS processes, higher responsivities, and higher modulation bandwidths [4]. Monolithically-integrated Ge-on-Si photodetectors with 265 GHz bandwidth and 100-200 nA dark currents have been demonstrated [5]; however, there are still many challenges to overcome before realising integrated Ge-based laser diodes. Hence, for Ge-on-Si, the problem is the reverse of that for QDs-on-Si, that is, a lack of efficient light sources as opposed to detectors. Bridging the gap in QD PD performance is a key challenge that, if overcome, could enable the realisation of fully monolithic QD-based transceivers on Si. One promising avenue for this is selective-area epitaxy, whereby the epitaxial material for active devices is grown in pockets on Si substrates [3]. In this context, there are benefits, relating to fabrication complexity and coupling efficiency, to packing as much functionality as possible into the III-V material. One key function of a PD in a transceiver PIC is laser diode optical power monitoring and, here, we present the results of an experimental study assessing the viability of using a monolithic QD PD as an optical power monitor for PICs.

II. Material & Methods

A. Epitaxial Structure

The epitaxial structures used in this study were designed for emission at 1310 nm. The active region consists of InAs QD layers, sandwiched between InGaAs capping layers with GaAs confinement layers in a dot-in-well configuration (DWELL). This is repeated in the structure 7 times. The active region is clad above by p-type AlGaAs and below by n-type AlGaAs. The structures are grown on n+ doped GaAs substrates.

B. Device Structure & Fabrication Process

The structure of the integrated optical monitor can be seen from the top-down microscope image in Fig. 1. The laser cavity is formed by 1- and 2-port multi-mode interference reflector (MMIR) mirrors. The reflectivity of the 1- and 2-port MMIRs are 90% and 50%, respectively [6]. The second port of the 2-port MMIR couples light into a waveguide which can be operated as an amplifier if electrically pumped. A fraction of the light in this waveguide is then coupled to the QD PD via a 2x2 multi-mode interferometer (MMI). In the case of Fig. 1, the PD is formed by a ring resonator. The majority of the light continues into an output waveguide with a cleaved facet from which the optical output can be collected. The output facet is angled by 10° to minimise back-reflections into the cavity. Additionally, the output waveguide can be operated as an amplifier if electrically pumped. In this study, the fraction of the light coupled into the QD PD was varied through different designs for the 2x2 MMI.

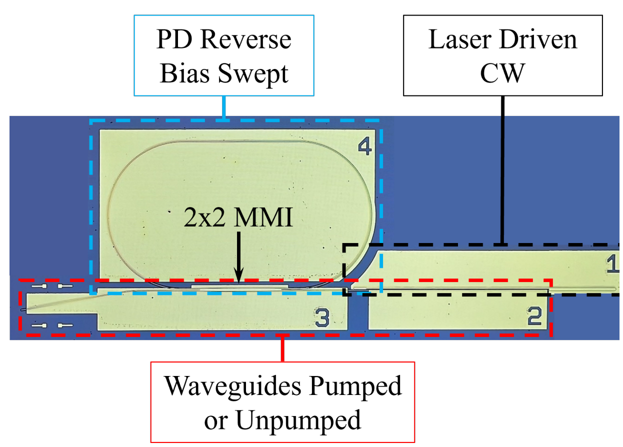

Fig. 1: Optical microscope image of the integrated optical power monitor. Section 1 is used to pumped the laser diode. Sections 2 and 3 are waveguides which can be operated as amplifiers. Section 4 is the photodiode, formed here by a ring resonator. A 2x2 MMI couples a fraction of the laser emission between sections and 3 and 4.

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For the fabrication, the laser diode, waveguides, and photodiode ridges are all defined simultaneously with a plasma dry etch. The sample is spin-coated with BCB and subsequently planarised to the height of the ridges with a second plasma dry etch. Ohmic contacts are formed on the top side (p-type) of the sample by physical vapour deposition of Ti/Au, and a global ohmic is formed by deposition of AuGe/Ni/Au contact to the substrate side (n-type), and subsequent anneal.

III. Experimental Method

The bias on the laser diode, waveguides, and photodiode are controlled independently with separate Keysight B2901a and Keithley 2401 source-measure units, all with a common ground. A continuous-wave (CW) current is swept across the laser diode and the optical power is measured from the angled facet. Light is coupled into a lensed single-mode fibre (SMF) which is mounted on a micro-positioner with six degrees of freedom. A range of reverse biases are applied to the QD PD section and the resulting photocurrent is measured. We also measure the inter-contact resistance between the sections to quantify leakage currents, which are subtracted from the photocurrents.

IV. Results

The optical power measured from the output waveguide facet is shown as a function of leakage-corrected CW laser pump current for increasing QD PD reverse bias in Fig. 2. These measurements were performed on a device with an 80:20 power split at the 2x2 MMI and with the waveguides unpumped (lossy) (sections 2 & 3 in Fig. 1). We observe that reverse biasing the PD has a minimal impact on the laser threshold current. The outcoupled power is on the order of 10s of µW due to the absorption loss in the waveguides and the coupling loss into the SMF. Considering the different sources of loss and comparing to previously fabricated MMIR lasers, we estimate the initial power emitted from the laser to be 2-4 mW at 30 mA injection current. The measured (leakage-corrected) current of the QD PD is shown as a function of reverse bias for increasing laser CW pump currents in Fig. 3.

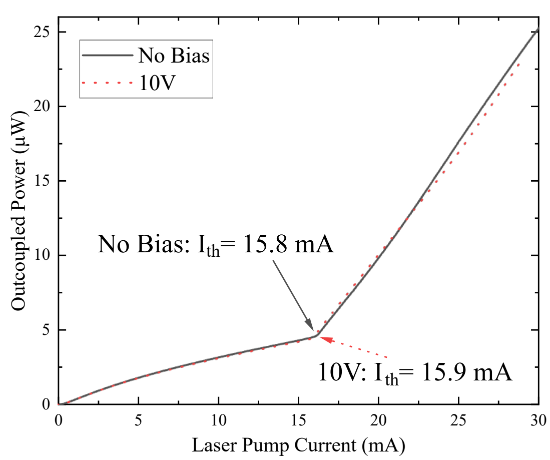

Fig. 2: Outcoupled power as a function of CW laser pump current measured from the angled facet for QD PD reverse biases from 0 to 10 V.

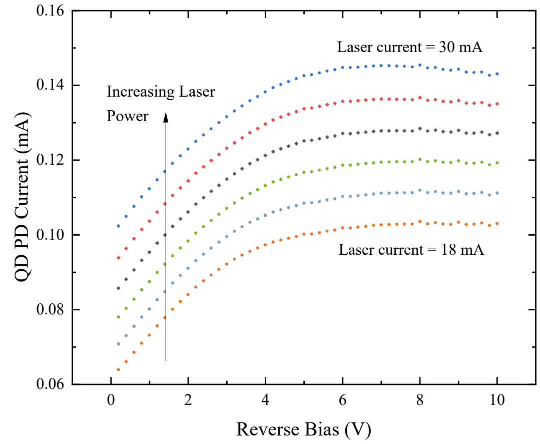

Fig. 3: Measured current of a ring resonator QD PD as a function of reverse bias shown for increasing CW laser currents.

We observe a saturation of the current between 4-5 V which is indicates the presence of photo-generated carriers and which demonstrates that light is coupling into the PD. The currents range from ~ 60 to 150 µA depending on the bias of the PD and on the output of the laser. Furthermore, we measure dark currents on the order of 10s nA, which is comparable to results previously reported for InAs QD photodetectors [7], [8].

Acknowledgment

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