# Monolithic Integration of 1.3 µm III-V Quantum-Dot Lasers on Si for Si Photonics

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**Abstract:** Quantum-dot (QD) lasers directly grown on Si are the prospective candidate to realize on-chip optical sources for Si photonics. In this paper, the recent progress made in field of Si-based QDs lasers are discussed.

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## 1. Introduction

Increased data throughput between silicon processors in modern information processing requires unprecedented bandwidth and low power consumption beyond the capability of conventional copper interconnects. To meet these requirements, Si photonics has been under intensive study in recent years. Unfortunately, because of the indirect bandgap structure of group IV materials, the abundant non-radiative recombination makes Si failed to be an effective light material for the optical light sources. In the contrast, III-V compounds with superior optical properties are the ideal gain material to generate the coherent light. Thus, the integration of III–V optoelectronic devices on Si will be the most practical way of obtaining on-chip light sources in Si photonics and the key to improving communication systems. In addition to the well-studied flip-chip and wafer bonding integration technologies, direct growth of III-V epitaxy materials on Si substrate seems more promising for low-cost and high yield in the long term.

Self-assembly formed III-V quantum dots (QDs) with three dimensional carrier confinement have been intensively promoted in order to achieve high performance III-V laser devices, in term of better defects tolerance, lower threshold current density and temperature-insensitive operation [1,2]. Very recently, the pioneering work of monolithic integration of III-V QD lasers on Si substrates have been demonstrated [1-4]. In this paper, we firstly describe high performance electrically pumped continues-wave (c.w.) operating InAs QD lasers epitaxially grown on a silicon substrate with an ultra-low threshold current density of 62.5 A/cm$^2$ and over 100,000 hours lifetime [2]. Secondly, we developed the first electrically pumped c.w. 1.3 µm InAs/GaAs QD lasers directly grown on microelectronics standard nominal (001) Si substrates without any intermediate buffers [4].

## 2. Long life III-V QD lasers on off-cut Si substrates

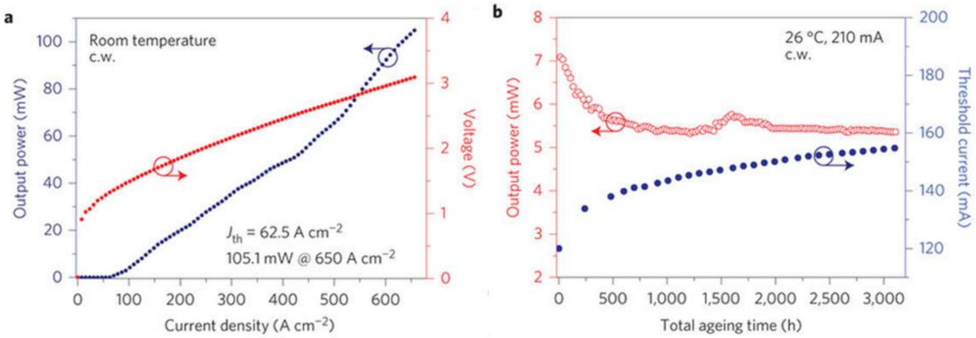

Fig. 1 (a). LIV curve of InAs/GaAs QD lasers on off-cut Si substrate under c.w. operation at room temperature; (b) Aging test of Si-based QD laser at a constant heatsink temperature of 26°C and 210 mA driving current.

InAs/GaAs QD laser structures were directly grown on phosphorus-doped Si substrates by a solid-source molecular beam epitaxy (MBE) system. The (001)-silicon wafer with 4° miscut-angle oriented towards the [011] plane was used to suppress antiphase domains (APDs). The combined strategies of an AlAs nucleation layer, InGaAs/GaAs dislocation filter layers (DFLs), *in situ* thermal annealing and using QDs as active regions are applied to realize the high quality GaAs-on-Si laser structure with low defects [2]. Figure 1 (a) shows light-current-voltage (LIV) measurement of this high performance QD laser on Si with a low threshold current density of 62.5 A/cm$^2$ and a room-temperature output power exceeding 105 mW under c.w. operation. The maximum lasing operation is up to 120 °C under pulsed condition. Figure. 1(b) shows the ageing data for this InAs/GaAs QD laser on silicon. The device was aged in auto current control mode at 26 °C under 210 mA of constant applied current. A sub-linear mode model is employed to fit the aging and an extrapolated lifetime of over 100,158 h was determined [2].

## 3. III-V QD lasers grown on "on-axis" (001) Si substrates

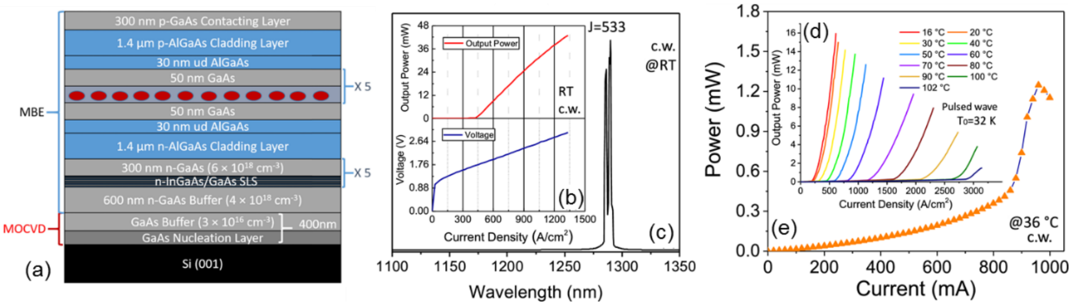

Fig.2. (a) Schematic diagram of InAs/GaAs on "on-axis" Si substrate growth layers by MOCVD and MBE; (b) LIV curve of an InAs/GaAs QD laser on nominal (001) Si substrate under c.w. operation at room temperature; (c) Lasing spectrum of the QD laser on Si when the injection current density is 533 A/cm$^2$; (d). L-I curves for a QD laser grown on Si (001) substrate at various temperatures under pulsed condition; (e). L-I curve for this Si-based InAs/GaAs QD laser at a heat sink temperature of 36 °C.

Figure 2 (a) shows the schematic diagram of the epitaxy structure of the QD laser on nominal (001) Si substrate, which was completed by both of metal-organic chemical vapor deposition (MOCVD) and MBE system. A GaAs nucleation layer was firstly deposited on 300 nm "on-axis" (001) Si substrate, followed by the GaAs buffer, both of layers being grown by MOCVD. After that, the wafer was then transferred to MBE for the succeeding III-V material growth. Epitaxy was then performed in the following order: a 600 nm GaAs buffer layer, five-period strained-layer superlattics (SLS) of InGaAs/GaAs DFLs, five layers of InAs/GaAs dot-in-well (DWELL) structures separated by 50 nm GaAs spacers between 1.4 µm n-type lower and p-type upper $Al_{0.4}Ga_{0.6}As$ cladding layers. Finally, a 300 nm p-type GaAs contact layer was grown. The broad area laser stripes was fabricated into varied 25 µm and 50 µm widths for testing.

Figure 2 (b) shows the LIV measurements for an InAs/GaAs QD laser grown on a silicon (001) substrate under c.w. operation at room temperature. A clear knee behavior in the light versus current (L-I) curve is observed at the lasing threshold of 425 A/cm$^2$. The measured single facet output power is 43 mW at an injection current density of 1.3 kA/ cm$^2$. The lasing spectrum measured at an injection current density of 533 A/cm$^2$ is shown in figure 2 (c), in which a lasing peak at 1288 nm is observed. Figure 2 (d) shows the L-I measurements of the QD laser on nominal (001) Si substrate at various heatsink temperature under pulsed wave operation. The maximum lasing temperature under pulsed condition is 102 °C, 32 K temperature characteristic was calculated between 16°C to 102 °C. Under c.w. operation as demonstrated in figure 2 (e), the Si-based QD laser has a maximum lasing operation at 36 °C due to the self-heating of the device. This strong temperature dependence could be improved by using modulation p-doping of the QD active region or/and a high thermal-conductivity heatsink

## 4. Conclusion

In conclusion, we have demonstrated high performance InAs/GaAs QDs lasers on offcut Si substrates with long lifetime (over 100,158 h) by MBE and the first electrically pumped c.w. InAs/GaAs QD lasers directly grown on on-axis GaAs/Si (001) substrates (without any intermediate buffer layers) with 425 A/cm$^2$ threshold current density and lasing operation to over 100 °C under pulsed condition.

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