# Scalable Heterogeneous Integration of a Pre-Processed Facet-Emitting Visible-Wavelength GaAs Laser

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**Abstract:** Heterogeneous integration of a pre-processed etched-facet GaAs multiple-quantum-well Fabry-Perot laser on silicon is shown through micro-transfer printing. Fiber-coupled output powers exceeding 3 mW at 789 nm are achieved with a threshold current of 60 mA. 

## 1. Introduction

Recently, a great push has been made to extend fully-integrated photonics to the shorter wavelength spectrum. At (near-)visible wavelengths, applications such as optical coherence tomography (OCT) and augmented reality/virtual reality (AR/VR) engines can be unlocked. Furthermore, light-matter interactions with rubidium at a wavelength of 780 nm allow for quantum applications such as Bose-Einstein condensation and the creation of optical clocks. Using silicon nitride (SiN) waveguides, passive circuits can be made to manipulate light at wavelengths well into the visible spectrum. To drive such circuits, separate gain materials such as gallium arsenide (GaAs) must be integrated to create lasers. This has been demonstrated at wavelengths around 970 nm through wafer-bonding of (Al)GaAs layers onto passive SiN circuits [1]. The other popular integration technique is micro-transfer printing [2], where pieces of material or complete devices measuring $< 100\ \mu$m by $\sim$1 mm can be integrated in a massively parallel manner. This has been shown reliably for indium phosphide (InP) at telecom wavelengths [3]. For 824 nm, GaAs epitaxial coupons were transfer printed on a silicon substrate and subsequently processed into edge-coupled Fabry-Perot lasers [4], showing great promise for integration of near-visible laser sources. However, the flexibility of this method is limited by the amount of processing necessary on the target sample. This work, instead, demonstrates integration of an etched-facet Fabry-Perot laser by micro-transfer printing fully-processed laser coupons. Fiber-coupled powers exceeding 3 mW are achieved at 789 nm with a treshold current of 60 mA.

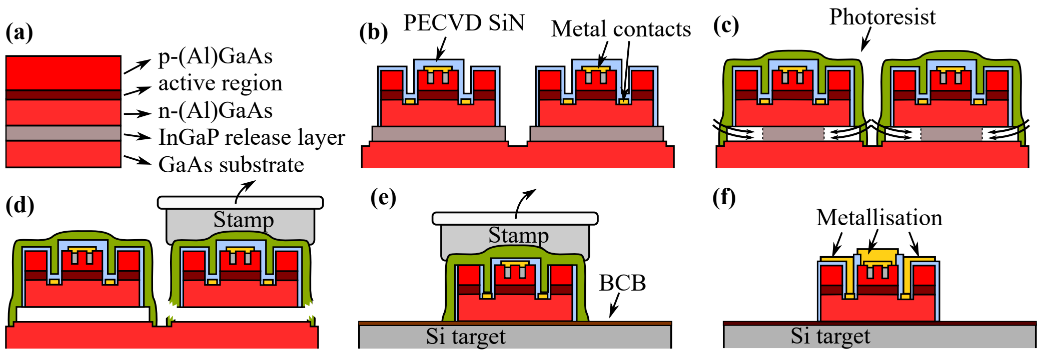


Fig. 1. Fabrication of transfer printed lasers: (a) Epitaxial layer stack. (b) Coupon fabrication, including metal contacts. (c) Encapsulation of laser coupons in photoresist and selective under-etch of InGaP release layer through holes in the photoresist. (d) Pick-up of laser coupon using a polymer stamp. (e) Printing of laser coupon on Si target substrate with a thin BCB adhesion layer. (f) Subsequent encapsulation removal and metallisation of contact pads.

## 2. Fabrication and Results

The fabrication process is outlined in Fig. 1. (Al)GaAs epitaxially grown layers on a GaAs substrate supplied by III-V Lab are processed to form ridge waveguide Fabry-Perot laser coupons measuring 1 mm long by 50 um wide. On the back facet of the coupon (not pictured), a broad-band gold mirror is deposited. The front-side of the coupon is etched to form the output facet of the cavity. The coupons are then micro-transfer printed onto a silicon target substrate, which is covered with a thin benzocyclobutene (BCB) adhesion layer, and post-printing-processed to form electrical contact pads. A 75 $\mu$m-deep step was etched in the target substrate within 10 micron of the laser facet to accommodate a lensed fiber to capture the laser emission. The sample was subsequently diced parallel to the etched step.

At 70 mA, scattered light was clearly visible with the naked eye, as shown in Fig. 2(a). Two printed lasers before post-printing-processing are shown in Fib. 2(b). In Fig 2(c), the light-current and voltage-current curves are plotted, showing a threshold current around 60 mA with a turn-on voltage around 1.4 V. A maximum fiber-coupled power of 3.4 mW was measured at 120 mA driving current. The corresponding laser spectrum is plotted in Fig. 2(d) along with sub-threshold amplified spontaneous emission (ASE) at 50 mA. Multiple longitudinal modes are visible, with a dominant mode at 788.7 nm showing around 10 dB of sideband suppression. The mode spacing of 76 pm corresponds to the free spectral range (FSR) of the 1 mm-long Fabry-Perot cavity.

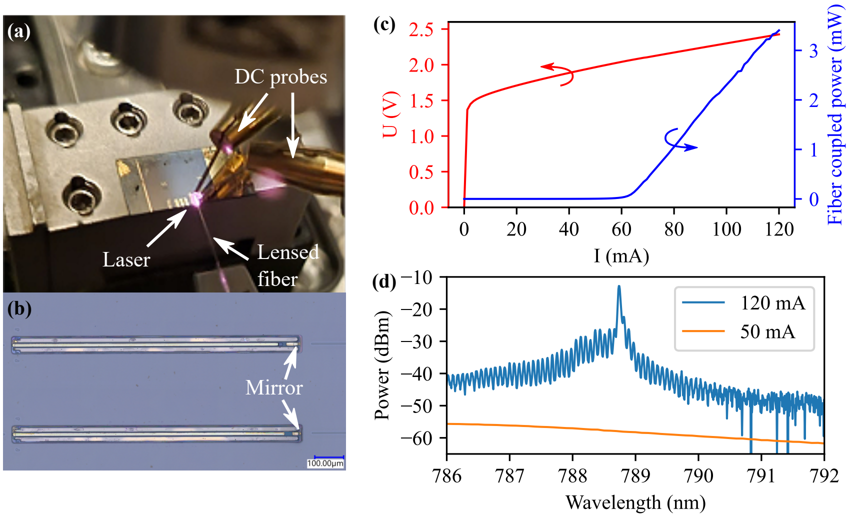


Fig. 2. (a) Measurement setup showing light emission at a driving current of 70 mA, visible by naked eye as red light. (b) Two printed lasers on Si before post-printing-processing. (c) Fiber-coupled power and bias voltage as a function of driving current. (d) Spectrum at 120 mA driving current (blue line) measured with 33 pm resolution compared to the ASE spectrum at 50 mA (orange line).

## 3. Conclusion and Outlook

We show heterogeneous integration of a facet-emitting GaAs Fabry-Perot laser through micro-transfer printing on a Si substrate achieving powers of more than 3 mW at a center wavelength of 788.7 nm. Printing fully-processed lasers offers great flexibility for integration and forms an important step towards integration of laser sources at wavelengths below 800 nm. This work shows promise to butt-couple to SiN waveguides for self-injection locking and extended-cavity lasers to form tunable single-mode laser sources for a wide range of applications.

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### References

1. M. A. Tran, C. Zhang, T. J. Morin *et al.*, "Extending the spectrum of fully integrated photonics to submicrometre wavelengths," Nature **610**, 54–60 (2022).
2. G. Roelkens, J. Zhang, L. Bogaert *et al.*, "Micro-Transfer Printing for Heterogeneous Si Photonic Integrated Circuits," IEEE J. Sel. Top. Quantum Electron. pp. 1–15 (2022).
3. C. Op de Beeck, B. Haq, L. Elsinger *et al.*, "Heterogeneous III-V on silicon nitride amplifiers and lasers via micro-transfer printing," Optica **7**, 386–393 (2020).
4. J. Justice, C. Bower, M. Meitl *et al.*, "Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers," Nat. Photonics **6**, 610–614 (2012).