InP Nanowire lasers Epitaxially Grown on (001) Silicon ‘V- groove’ templates

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Abstract—**We demonstrate an ultra-low threshold nanowire laser monolithically integrated on a (001) silicon substrate. By using a V-groove template we were able to reduce the laser threshold by one order of magnitude (0.19pJ per pulse) compared with our earlier devices and dramatically increased the yield throughout the wafer.**

I. INTRODUCTION

Silicon photonics has been proven to be an outstanding platform for telecom and datacom since it was introduced nearly a decade ago and is now also investigated for its potential for bio-sensing and non-linear applications. Efficient light emission directly from silicon has not yet been demonstrated and therefore typically III-V based devices are integrated wherever an on-board light source is required. Methods based on flip-chip [1], wafer bonding [2-4] and transfer printing [5] have been investigated for almost a decade now, but despite many successes, still suffer from poor heat sinking, a non-standard process flow and the corresponding performance and cost limitations. Therefore, to achieve compact integrated lasers with better performance (good heat dissipation, lower power consumption, and lower cost) monolithic integration based on selective area epitaxial growth was proposed. However, InP, typically used for telecom band devices, has a 8.1% lattice mismatch with silicon. Several solutions have been proposed recently to avoid the threading dislocations and anti-phase boundaries (APB) originating from this mismatch [6-8]. Previously we reported a polytypic InP nano-cavity laser epitaxially grown on (001) Silicon [9] using a step-surface-Germanium seed layer to eliminate the anti-phase boundaries (APB) [10]. In that case however, only a very limited fraction of the devices formed the desired nanowire shape and exhibited laser operation. Here we present improved yielding of the nanowire growth and material quality by using ‘V-groove’ templates [11], which improve the nucleation of InP in trenches [12]. APBs can only form at the trench corners and are blocked by burying the corner before heteroepitaxy.

II. FABRICATION

To prepare the V-groove templates, first 40nm by 200nm rectangular openings were defined on 300nm-thick oxide layer on a (001) silicon wafer using a standard shallow trench isolation (STI) process. Next V-grooves were formed at the bottom of the STI-trenches in a wet etching process (5% TMAH solution at 80° C). Prior to the epitaxial growth, the wafer was etched by HF and baked in H_2 at high temperature for 10 minutes to remove the native oxide layer. During the cooling down, tertiarybutylarsine (TBAs) was introduced to passivate the {111}Si surface. The main growth is performed in a two steps metal–organic vapor phase epitaxy process (MOVPE). First a low temperature growth forms a stable InP nucleation layer, then a high temperature process results in an epilayer with high crystalline quality. Figure 1(a) shows a typical scanning electron microscopy image of the InP nanowires grown on top of the template. The hexagonal outer shape and the uniform tilted angle with respect to the sample surface prove that these are typical InP nanowires inclining to the [111] crystalline direction. Fig.1 (b) shows a SEM image of the sample surface. Around 35 out of 80 sites exhibit the desired nanowire shape, which is an improvement by up to two orders of magnitude compared to our earlier work [9] using Ge-based seeds. These results hold for most parts of the wafer.

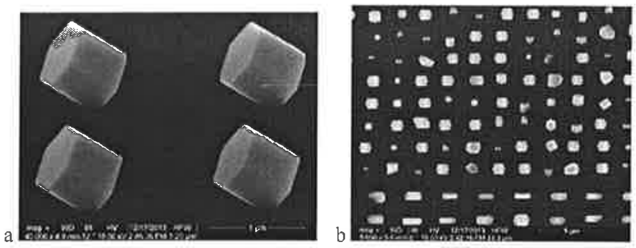

Figure 1. a) Tilted SEM picture demonstrating pillars with similar shapes and dimensions. b) An SEM top view of a random location from the sample. Note that the bottom two rows had a different mask opening size.

III. CHARACTERIZATION RESULTS

Optical characterization of the InP-on-Si nanowires was performed on a micro-photoluminescence (PL) setup using a ×50, 0.6 numerical aperture objective both to deliver the pump light and to collect the emitted light . The PL signal was resolved by a 1/4 m monochromator with a TE-cooled silicon detector. For wide area PL measurements the diameter of the pumping area was around 20μm, while for single laser characterization the pumping spot was reduced to 3μm.

APB free III-V material grown on a Si(111) surface was demonstrated by several groups before but twins and stacking faults are inevitable in most cases [7-8]. The PL spectrum of a single pillar under CW pumping using a 532nm Nd:YAG laser (dashed line in Fig. 2(a)) shows that the peak is slightly blue

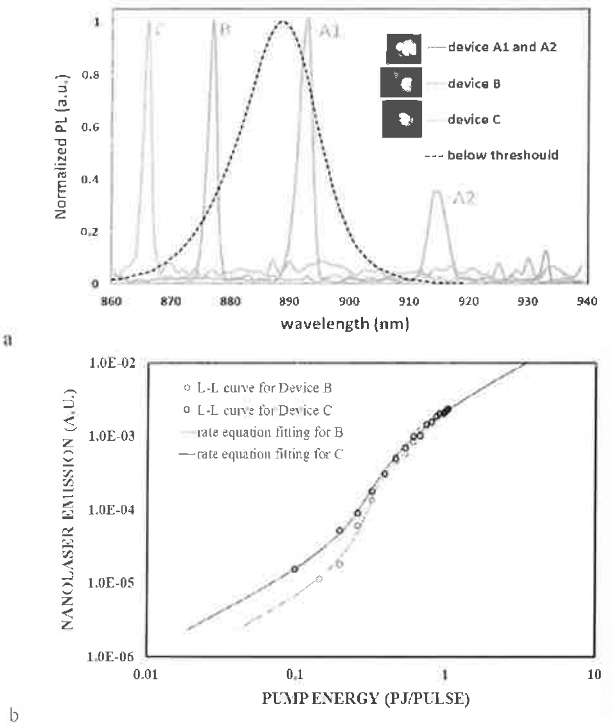

Figure 2. a) Normalized PL of different devices (solid colored lines) above threshold under pulsed pumping. The blue line originates from two devices, A1 and A2, too close to be resolved separately. The black dashed line shows the normalized PL below threshold (CW pumping). b) L-L curves of devices B and C at room temperature under pulsed pumping. Circles denote the measured points. From a rate equation fitting (solid lines) a threshold of 0.21pJ and 0.19pJ was extracted for device B and C respectively.

shifted from the PL of pure Zincblende InP at room temperature [13]. As discussed in our previous work, this effect mainly comes from the polytypic crystal property of the nanowires: super-lattice like heterostructures are formed by packing of Zincblende and Wurtzite InP crystal phases, and the corresponding quantum confinement blue shifts the bandgap. Under pulsed optical pumping using a Nd:YAG 532 nm laser with 7ns pulses at 259Hz repetition rate, lasing is obtained for a large fraction of the InP-on-Si nanowires.

Fig. 2(a) shows the normalized PL spectra of different nanowire lasers above threshold, and the insets are the corresponding PL images. Also in terms of laser yield we find A dramatic increase using the 'V-groove' template compared to our earlier results. A PL image of a random area on the sample, as shown in Fig. 3, shows densely spaced working nanowires within the 20μm-diameter pumped area.

IV. DISCUSSIONS AND CONCLUSION

As shown previously by FDTD simulations [9], the optical modes that are supported by these tilted nanowires are helically propagating modes. Although these cavities are much shorter compared with other nanowire lasers, optical modes with Q-factors up to 150 are supported. Thanks to their limited size only a few modes exist in the wavelength range of the gain spectrum, resulting in a large spontaneous emission factor (β) (we extracted a value β = 0.06-0.075 from the results shown in Fig 2b). This high β is essential for laser threshold reduction.

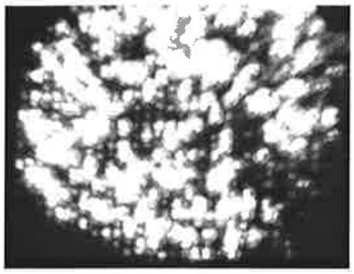

Figure 3. The PL image pumped by pulsed laser, and the diameter of the pumping area is around 20μm.

In summary, we improved the growth yield and reduced the threshold of InP nanowire lasers compared to our earlier work by switching to 'V-groove' templates. The device becomes much simpler to fabricate, more robust and promising for applications, such as bio-sensing and optical quantum communication.

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	Sunday, 11 May
13h30–14h30	Room C Short course A
15h	Break
15h30–16h30	Room C Short course B
17h–17h30	CSW Registration
18h–19h30	Welcome Reception

	Monday, 12 May			
8h30	Opening			
9h	Plenary 1			
9h30	Plenary 2			
10h	coffee break 10h15-10h45			
11h	Plenary 3			
11h30	Plenary 4			
12h30	Lunch - 12h30-13h30h			
13h30	Mo-A1 ISCS	Mo-B1 IPRM	Mo-C1 IPRM	Mo-D1 ISCS
14h	GaN Prospective	Phot. Integ.1	Elec. Dev.1	NW Growth
15h	coffee break 15h-15h30			
15h30	Mo-A2 IPRM	Mo-B2 IPRM	Mo-C2 ISCS	Mo-D2 ISCS
16h	Epi.-Nano. 1	Opto.1	Oxydes - Electro. Opt	Carbon-flexible
17h	Poster session/beers/wines -17h-19h			

	Tuesday, 13 May			
8h30	Tu-A1 ISCS	Tu-B1 IPRM	Tu-C1 ISCS	Tu-D1 ISCS
9h	Solar	Elec. Dev2	Oxydes	Epi. & Mat for advanced devices
10h30	coffee break 10h30-11h			
11h	Tu-A2 ISCS	Tu-B2 ISCS	Tu-C2 ISCS	Tu-D2 IPRM
11h30	GaN NW and UV	MIR-ThZ	Physics - Transport	Epi.-Nano. 2
13h	Lunch - 13h-14h00			
14h	Tu A3 ISCS	Tu-B3 ISCS	Tu-C3 ISCS	Tu-D3 IPRM
14h30	Lasers	QW-QD Growth	In-based nitride mat. & dev.	Opto.2
15h30	Coffee break 15h45-16h15			
16h	IPRM/ISCS award ceremony - 16h15-17h			
17h	Rump session 17h-19h			

	Wednesday, 14 May			
8h30	We-A1 ISCS	We-B1 IPRM	We-C1 ISCS	We-D1 ISCS
9h	µcavities & NW-lasers	Phot. Integ.2	Physics-optics	High-Frequency
10h30	coffee break 10h30-11h			
11h	We-A2 ISCS	We-B2 ISCS	We-C2 ISCS	We-D2 IPRM
11h30	Zn based oxydes	Nanocharac	Nitrides on Si & Photon	Phot. Integ.3
13h	Excursion 13h -18h (lunch is provided)			
19h	Conference dinner 19h-22h			

	Thursday, 15 May			
8h30	Th-A1	Th-B1 IPRM	Th-C1 ISCS	Th-D1 ISCS
9h	Post-deadline	Epi.-Nano.3	N-based devices 1	Photo detector
10h30	coffee break 10h30-11h			
11h	Th-A2 ISCS	Th-B2 IPRM	Th-C2	Th-D2 IPRM
11h30	N-based devices 2	Opto.3	Post-deadline	Elec. Dev.3
12h30	Closing and Student Award ceremony 12h45-13h15			

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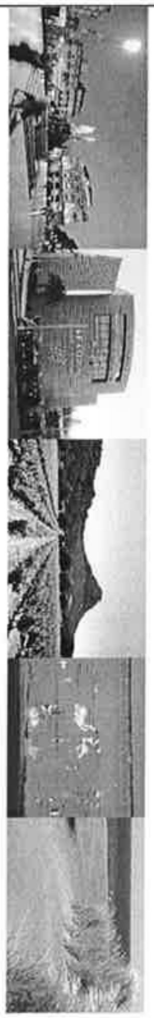

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