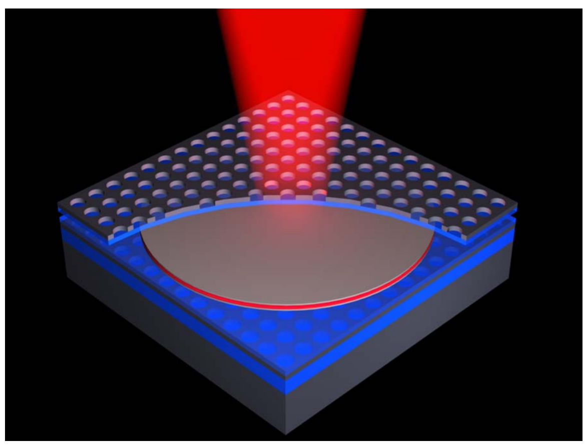
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access
Invited Paper

Breakthroughs in Photonics 2012: Breakthroughs in Nanomembranes and Nanomembrane Lasers

Volume 5, Number 2, April 2013

Weidong Zhou, Senior Member, IEEE
Zhenqiang Ma, Senior Member, IEEE



DOI: 10.1109/JPHOT.2013.2250942
1943-0655/$31.00 ©2013 IEEE

Breakthroughs in Photonics 2012: Breakthroughs in Nanomembranes and Nanomembrane Lasers

Weidong Zhou,[1] *Senior Member, IEEE*, and Zhenqiang Ma,[2] *Senior Member, IEEE*

(Invited Paper)

[1]Department of Electrical Engineering, NanoFAB Center, University of Texas at Arlington, Madison TX 76019 USA
[2]Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison WI 53706 USA

DOI: 10.1109/JPHOT.2013.2250942

Manuscript received February 8, 2013; accepted February 23, 2013. Date of publication March 7, 2013; date of current version May 2, 2013. Corresponding author: W. Zhou (e-mail: wzhou@uta.edu).

Abstract: Crystalline semiconductor nanomembranes (NMs) offer unprecedented opportunities for unique electronic and photonic devices for vertically stacked high-density photonic/ electronic integration, high-performance flexible electronics, and adaptive flexible/conformal photonics. We present here major progresses reported over the last year, in the area of semiconductor NM photonics, with focuses on the innovative membrane laser devices and structures for silicon photonics and flexible optoelectronics.

Index Terms: Semiconductor nanomembrane (NM), semiconductor lasers, vertical-cavity surface-emitting laser (VCSELs), membrane lasers, Fano resonance, photonic crystals, membrane reflectors (MRs), silicon photonics, flexible electronics, flexible photonics, bio-integrated electronics.

1. Introduction

Inorganic crystalline semiconductor nanomembranes (NMs, freestanding sheets with nanometer to submicrometer scale thicknesses) have, in the the last several years, demonstrated great potential to become a disruptive technology, which is primarily driven by the successes shown with group IV crystalline NMs transferred and stacked onto foreign substrates, including both rigid (e.g., silicon and glass) and flexible (e.g., plastics and polymers) substrates [1]–[12]. The drivers for this potential are the inherently novel electronic and mechanical properties of these sheets; their flexibility, conformability, biocompatibility, and transferability to other hosts; the ability to introduce strain (and, thus, novel properties associated with strain) in ways not possible with bulk materials; and the ability to integrate membranes of different materials because of the much better bondability of membranes than bulk material.

Based on this disruptive NM platform, a new class of photonic structures and devices has been demonstrated. Here, we review major progresses made in 2012, in the area of NM photonics, with focuses on NM lasers and other photonic devices for applications in silicon photonics and flexible optoelectronics.

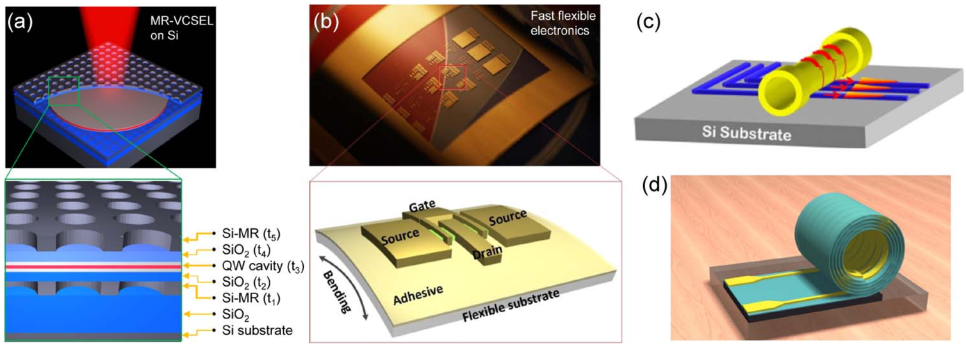


Fig. 1. NM-enabled photonic and electronic devices. (a) MR-VCSEL on Si [12]. (b) Si NM-based fast flexible transistors with record speed [31]. (c) and (d) NM roller-up tubes for (top) light sources [32] and (bottom) electronic inductors [33].

2. Membrane Lasers for On-Chip Silicon Photonics

The creation of practical light sources on elementary silicon (Si) substrates has proven to be a major roadblock toward large-volume low-cost integrated photonics and electronics on Si substrates. [13] Among numerous approaches reported so far, one of the most paths toward lasing on Si based on the heterogeneous integration of Si with compound semiconductor materials, where emission comes from efficient direct band gap (e.g., group III–V) materials. These Si-based lasers have been reported with promising performances, either based on direct growth of III–V materials on Si [14]–[16] or direct wafer bonding to Si [17]–[21]. Owing to the stackability of NMs based on PDMS transfer printing processes, which is originally developed by Meitl *et al.* [22], heterogeneous integration of dissimilar materials becomes very promising with very encouraging results reported over the last year, including the demonstrations of membrane lasers on Si [12], [23]. Reported in the same issue of *Nature Photonics* [24], two independent research groups reported III–V/Si hybrid integrated edge-emitting and surface-emitting membrane lasers on Si. In both cases, the high-quality III–V quantum-well (QW) active region was released from the original III–V growth substrate and subsequently transferred onto the foreign Si substrates via PDMS stamp printing transfer technique, Justice *et al.* [23] reported an electrically driven AlGaAs/AlInGaAs double QW Fabry–Perot edge-emitting laser on Si. The QW active region was first grown on its native GaAs substrate with an additional AlGaAs sacrificial layer. After selective etching of the AlGaAs sacrificial layer, the epitaxial active lasing cavity structure (NM) was released from the GaAs substrate, and transfer printed onto a Si substrate, via the PDMS transfer printing technique. The complete laser cavity fabrication, including cavity facet etching and metal electrodes formation, was carried out after the transfer of the epitaxial AlGaAs/AlInGaAs QW NM onto the Si substrate. The authors reported very impressive lasing performance with lasing wavelengths of 824 nm and operation temperature up to 100 °C.

An optically pumped membrane reflector vertical-cavity surface-emitting laser (MR-VCSEL) on silicon was reported from our groups, [12] based on the multilayer semiconductor NM stacking via a stamp transfer printing process. As schematically shown in Fig. 1(a), MR-VCSEL on Si consists of a transferred III–V InGaAsP QW heterostructure that is sandwiched in-between two thin single-layer silicon photonic-crystal Fano resonance MRs (Si-MRs) [25]–[27]. These Si-MRs essentially replace the two multilayer quarter wavelength DBR (distributed Bragg reflector) mirrors that are commonly used in conventional VCSELs [28]–[30]. The use of MRs results in the lasers to be directly built on Si substrates with much reduced laser size (height), leading to a complete near infrared (NIR) MR-VCSEL cavity thickness to be less than 2 μm [for a total of five layers t_1 to t_5, as defined in Fig. 1(a)]. The unique laser features not only enable high-performance lasers on Si, but also enable a planar cavity structure allowing much simpler integration schemes with CMOS electronics. Such an ultrathin cavity also has a much tighter field distribution than DBR-based VCSELs, with significantly reduced energy penetration depth and reduced cavity lengths [27]. By further reducing the lateral cavity size down to a few micrometers with proper lateral confinement, such MR-VCSEL can have greatly reduced power consumption, improved power efficiency and higher modulation speed.

Different from the conventional DBR-based VCSEL bonded/transferred onto Si substrates after complete laser fabrication, the multilayer membrane transfer printing process offers a very simple and agile approach to large-scale photonic integration. The fabrication procedure is scalable to full wafer size. In addition, different from the wafer-fusing/bonding approaches, the transfer-printed multilayer membranes can have different types of interface control and engineering measures, allowing better thermal mismatch tolerance between dissimilar materials, and, thus, better thermal performance and better device reliabilities. With this demonstrated approach to lasers on Si, different material systems can now be integrated together, with unlocked constraints in lattice mismatches and thermal mismatches, opening doors toward a wide range of applications in optoelectronic and photonic devices and integrated systems thereof. The ultracompact high-finesse Fabry–Perot cavity, based on two parallel single-layer Si-MRs, offers a simple solution to VCSELs on Si and on any other substrates. The planar laser structure and the compact cavity sizes are highly desirable for high-density photonic and electronic integration on Si. Such a cavity configuration can also offer a very cost-effective solution to long-wavelength VCSEL laser technologies, from near infrared to far infrared and beyond. The approach also renders wavelength scalability and tenability. Thus, multiwavelength MR-VCSEL arrays can also be realized on Si substrates, based on the control of the MR lattice parameters and the membrane material transfer printing ability. Notably, the MR-VCSEL devices can be further integrated with different functional photonics NM layers for modulation, beam focusing and routing, and photonic/electronic integration. Lastly, the MR-VCSEL devices can be built and transferred onto any other rigid glass or flexible plastic substrates, making them even more attractive for applications in consumer electronics and bio-photonics [12].

3. Flexible NM Optoelectronics

Another technology area poised for significant growth is flexible large-area electronics and photonics. Such devices have applications ranging from flexible imaging, displays, energy-efficient lighting, solar cells, sensors, and conformal electronic/photonic integrated systems to potential integration into artificial muscles or biological tissue. Traditionally, flexible electronics and photonics are based on organic or low-temperature-deposited amorphous semiconductor (a-Si) materials, processed with a large-area printing technique or other simple deposition techniques. The ability to synthesize and extremely manipulate thin films of solid-state materials (e.g., crystalline NMs) enables an entirely new approach to high-performance (speed) flexible electronics and flexible photonics [34]–[36]. The uses of the NMs include adaptive communication/surveillance systems, compact antennas conformally attached to morphing aircrafts and missiles, flexible sensors for structural health monitoring, flexible communications, and wearable electronics and smart soldier uniforms with dynamic threat responses [37], [38].

Based on transfer-printed NMs on flexible substrates, various high-performance photonic and electronic devices have been demonstrated, including flexible photodetectors, LEDs, and solar cells, flexible Si Fano resonance filters, and mostly significantly, fast flexible electronics, with record speed of RF performances, owing to high electron mobility in single crystalline semiconductors. [7], [9], [10], [31], [37], [39]–[47]. To improve the yield of the printing transfer process, Xu *et al.* [48] reported an innovative stamp printing technique with an adhesion controllable suspended configuration. High-performance SiNM photonic waveguides on flexible substrates were demonstrated, with propagation loss of $\sim$1.1 dB/cm, comparable with waveguides on SOI. To address the alignment challenge over the large-area flexible substrate, a local alignment scheme in combination with more accurate SiNM transfer measures for minimizing alignment errors was reported. [31] By realizing 1-μm channel alignment for the SiNMs on a soft plastic substrate, thin-film transistors with a record speed of 12-GHz maximum oscillation frequency were demonstrated [Fig. 1(b)]. Recently, based on strained Si/SiGe/Si NMs transferred onto a flexible substrate, another record was set for fast flexible transistors with a maximum oscillation frequency of 15 GHz was demonstrated [49]. These results indicate the great potential of properly processed SiNMs for high-performance flexible electronics, opening doors for a wide range of applications for high-speed flexible/conformal RF systems [9].

4. Strain-Engineered NMs

The controlled introduction of strain in suspended NMs offers important degrees of freedom for engineered material properties [1], [6], [49], [50]. One of the direct consequences of strained NMs is the formation of complex 3-D shaped structures, such as ribbons and rolled-up tubes [3]. Many impressive works have been reported earlier, including rolled-up tube arrays [5], optofluidic tube arrays for bio-molecular sensing [51], rolled-up NM tube inductors [33], and rolled-up tube cavity-based nanolasers [Fig. 1(c) and (d)] [32], [52].

It is also well known that strain in a crystalline solid modifies the lattice constants and reduces the crystal symmetry, leading to a significant shift in the energy band edges and often accompanied by a splitting of degenerate states. The ability to alter the strain, in magnitude, direction, spatial extent, periodicity, symmetry, and/or nature, allows tuning of the intrinsic properties to such a degree that many are significantly modified, including band structure, charge carrier mobility, atomic transport, atomic defect structure, the self-assembly of quantum dots (QDs), piezoresistivity, and more complex phenomena such as electrooptical effects [6], [50], [53], [54].

Based on the strained Ge grown on Si and n-type doping in the active region, Ge lasers on Si have been recently reported [55]. A few other groups also reported the light emission properties from Ge NMs with controlled strain [56]. Direct-band-gap light emission was observed in biaxial tensile strained Ge NMs, where the emission spectra show a red shift with the increase in strain in suspended Ge NMs [57]. Nam *et al.* [58] presented a novel method to introduce a sustainable biaxial tensile strain larger than 1% in a thin Ge NM using a stressor layer integrated on a Si substrate. Raman spectroscopy confirmed that 1.13% strain and photoluminescence show a direct band-gap reduction of 100 meV with enhanced light emission efficiency. Simulation results predict that a combination of 1.1% strain and heavy n+ doping reduces the required injected carrier density for population inversion by over a factor of 60. With active strain control via piezoelectric actuators, Trotta *et al.* [4] reported a novel strain-tunable LED structure, where NM QD LED structure was integrated onto piezoelectric actuators for nonclassical light emission with adjustable properties, with potential applications toward absolute control over fine structure splitting between the bright excitonic states and quantum computing.

5. NM Integrated Systems

Over the last year, we also see significant activities in NM-based integrated systems for computing, communication, and bio-integrated system applications. In addition to various lights sources being explored based on NM materials, other photonic devices are being explored for integrated electronic/photonic systems. A subwavelength grating (SWG) coupler for coupling light efficiently into in-plane semiconductor NM photonic devices was reported by Subbaraman *et al.* [59], based on Si-NM transferred onto a glass substrate. The SWG grating coupler on glass reaches a coupling efficiency of 39.17% at 1555.56 nm, with a 1-dB bandwidth of 29 nm. Double-layer stacked 1×12 multimode interference couplers were also demonstrated based on SiNMs for potential applications in vertically integrated 3-D photonics [60].

Many reports appeared over the last year, in the area of NM-based bio-integrated flexible devices and systems, where high-performance semiconductor device functionality can be achieved in forms that enable intimate conformal contacts to flexible/conformal surfaces. Kim *et al.* [61], [62] presented a flexible/stretchable system of InGaN microscale transfer-printed inorganic LEDs with wireless powering schemes for implantable devices that could be used to accelerate wound healing, activate photosensitive drugs, or to perform imaging and spectroscopic characterization of internal tissues [63]. Along the direction of bio-integrated electronics, a physically transient form of silicon electronics was proposed by Hwang *et al.* [2], where NM devices are built on bio-resorbable substrates (e.g., silk), and the complete material system physically disappears at prescribed times and at controlled rates. An implantable transient device that acts as a programmable nonantibiotic bacteriocide was demonstrated and sealed in silk packages. Based on tubular rolled-up strained SiO_2 NM optofluidic ring resonators (RU-OFRRs), Harazim *et al.* [51] reported a lab-in-a-tube label-free optofluidic sensing system on a glass substrate. The quality factors for the fabricated RU-OFRR approaches 2900. The sensitivity of the integrated RU-OFRR, which is the response of the modes to the change in refractive index of the liquid, is up to 880 nm/refractive index units.

6. Summary

Significant progresses have been made in the exciting and emerging field of NMs. Here, we only offer a highlight of a small portion of the work being reported over the last year. We envision that much more progresses and breakthroughs will continue to be reported in the years to come. The emerging field of NM photonics and electronics holds great promises toward materials with new physical properties, devices with unique structures and performances, and innovative integrated systems with great scientific impact and technological potentials.

Acknowledgment

The authors would like to thank the help and support from U.S. AFOSR (Dr. G. Pomrenke) and U.S. ARO (Dr. M. Gerhold).

References

[1] J. A. Rogers, M. G. Lagally, and R. G. Nuzzo, "Synthesis, assembly and applications of semiconductor nanomembranes," *Nature*, vol. 477, no. 7362, pp. 45–53, Aug. 2011.
[2] S. W. Hwang, H. Tao, D. H. Kim, H. Cheng, J. K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, and Y. S. Kim, "A physically transient form of silicon electronics," *Science*, vol. 337, no. 6102, pp. 1640–1644, Sep. 2012.
[3] O. G. Schmidt and K. Eberl, "Nanotechnology: Thin solid films roll up into nanotubes," *Nature*, vol. 410, no. 6825, p. 168, Mar. 2001.
[4] R. Trotta, P. Atkinson, J. Plumhof, E. Zallo, R. Rezaev, S. Kumar, S. Baunack, J. Schröter, A. Rastelli, and O. Schmidt, "Nanomembrane quantum light emitting diodes integrated onto piezoelectric actuators," *Adv. Mater.*, vol. 24, no. 20, pp. 2668–2672, May 2012.
[5] X. Li, "Self-rolled-up microtube ring resonators: A review of geometrical and resonant properties," *Adv. Opt. Photon.*, vol. 3, no. 4, pp. 366–387, Dec. 2011.
[6] S. A. Scott and M. G. Lagally, "Elastically strain-sharing nanomembranes: Flexible and transferable strained silicon and silicon–germanium alloys," *J. Phy. D, Appl. Phys.*, vol. 40, no. 4, pp. R75–R92, Feb. 2007.
[7] H. C. Yuan, Z. Ma, M. M. Roberts, D. E. Savage, and M. G. Lagally, "High-speed strained-single-crystal-silicon thin-film transistors on flexible polymers," *J. Appl. Phys.*, vol. 100, no. 1, pp. 013708-1–013708-5, Jul. 2006.
[8] L. Sun, G. Qin, J. H. Seo, G. K. Celler, W. Zhou, and Z. Ma, "12 GHz thin film transistors on transferrable silicon nanomembranes for high performance flexible electronics (cover story)," *Small*, vol. 6, no. 22, pp. 2553–2557, Nov. 2010.
[9] K. Zhang, J. H. Seo, W. Zhou, and Z. Ma, "Fast flexible electronics using transferrable silicon nanomembranes (Topical Review)," *J. Phys. D, Appl. Phys.*, vol. 45, no. 14, p. 143 001, Apr. 2012.
[10] W. Zhou, Z. Ma, H. Yang, Z. Qiang, G. Qin, H. Pang, L. Chen, W. Yang, S. Chuwongin, and D. Zhao, "Flexible photonic-crystal Fano filters based on transferred semiconductor nanomembranes," *J. Phys. D, Appl. Phys.*, vol. 42, no. 23, p. 234007, Dec. 2009.
[11] W. Zhou, Z. Ma, H. Yang, L. Chen, W. Yang, Z. Qiang, G. Qin, H. Pang, S. Chuwongin, and D. Zhao, "Semiconductor nanomembranes for stacked and flexible photonics (Invited)," in *Proc. SPIE*, 2010, p. 76060U.
[12] H. Yang, D. Zhao, S. Chuwongin, J. H. Seo, W. Yang, Y. Shuai, J. Berggren, M. Hammar, Z. Ma, and W. Zhou, "Transfer-printed stacked nanomembrane lasers on silicon," *Nat. Photon.*, vol. 6, no. 9, pp. 615–620, Sep. 2012.
[13] L. Pavesi, "Will silicon be the photonic material for the third millenium?" *J. Phys. Conden. Mat.*, vol. 15, no. 26, pp. R1169–R1196, Jul. 2003.
[14] Z. Mi, P. Bhattacharya, J. Yang, and K. P. Pipe, "Room-temperature self organized $In_{0.5}Ga_{0.5}As$ quantum dot laser on silicon," *Electron. Lett.*, vol. 41, no. 13, pp. 742–744, Jun. 2005.
[15] G. Balakrishnan, A. Jallipalli, P. Rotella, S. Huang, A. Khoshakhlagh, A. Amtout, S. Krishna, L. R. Dawson, and D. L. Huffaker, "Room-temperature optically pumped (Al) GaSb vertical-cavity surface-emitting laser monolithically grown on an Si (1 0 0) substrate," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 6, pp. 1636–1641, Nov./Dec. 2006.
[16] R. Chen, T. T. D. Tran, K. W. Ng, W. S. Ko, L. C. Chuang, F. G. Sedgwick, and C. Chang-Hasnain, "Nanolasers grown on silicon," *Nat. Photon.*, vol. 5, no. 3, pp. 170–175, Mar. 2011.
[17] J. E. Bowers, H. Park, A. W. Fang, O. Cohen, R. Jones, and M. Paniccia, "Design and fabrication of optically pumped hybrid silicon-AlGaInAs evanescent lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 6, pp. 1657–1663, Nov./Dec. 2006.
[18] C. Seassal, P. Rojo-Romeo, X. Letartre, P. Viktorovitch, G. Hollinger, E. Jalaguier, S. Pocas, and B. Aspar, "InP microdisk lasers on silicon wafer: CW room temperatureoperation at 1.6 μm," *Electron. Lett.*, vol. 37, no. 4, pp. 222–223, Feb. 2001.

[19] C. Sciancalepore, B. B. Bakir, X. Letartre, J. Harduin, N. Olivier, C. Seassal, J. Fedeli, and P. Viktorovitch, "CMOS-compatible ultra-compact 1.55-um emitting VCSELs using double photonic-crystal mirrors," *IEEE Photon. Technol. Lett.*, vol. 24, no. 6, pp. 455–457, Mar. 2012.

[20] S. Stankovic, R. Jones, M. Sysak, J. Heck, G. Roelkens, and D. Van Thourhout, "1310 nm hybrid III-V/Si Fabry–Perot laser based on adhesive bonding," *IEEE Photon. Technol. Lett.*, vol. 23, no. 23, pp. 1781–1783, Dec. 2011.

[21] G. Roelkens, L. Liu, D. Liang, R. Jones, A. Fang, B. Koch, and J. Bowers, "III-V/silicon photonics for on-chip and intra-chip optical interconnects," *Laser Photon. Rev.*, vol. 4, no. 6, pp. 751–779, Nov. 2010.

[22] M. A. Meitl, Z. T. Zhu, V. Kumar, K. J. Lee, X. Feng, Y. Y. Huang, I. Adesida, R. G. Nuzzo, and J. A. Rogers, "Transfer printing by kinetic control of adhesion to an elastomeric stamp," *Nat. Mater.*, vol. 5, pp. 33–38, Jan. 2006.

[23] J. Justice, C. Bower, M. Meitl, M. B. Mooney, M. A. Gubbins, and B. Corbett, "Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers," *Nat. Photon.*, vol. 6, no. 9, pp. 610–614, Sep. 2012.

[24] R. W. Kelsall, "Hybrid silicon lasers: Rubber stamp for silicon photonics," *Nat. Photon.*, vol. 6, no. 9, pp. 577–579, Sep. 2012.

[25] S. Fan and J. D. Joannopoulos, "Analysis of guided resonances in photonic crystal slabs," *Phys. Rev. B*, vol. 65, no. 23, pp. 235112-1–235112-8, Jun. 2002.

[26] H. Yang, S. Chuwongin, Z. Qiang, L. Chen, H. Pang, Z. Ma, and W. Zhou, "Resonance control of membrane reflectors with effective index engineering," *Appl. Phys. Lett.*, vol. 95, no. 2, pp. 023110-1–023110-3, Jul. 2009.

[27] D. Zhao, Z. Ma, and W. Zhou, "Field penetrations in photonic crystal Fano reflectors," *Opt. Exp.*, vol. 18, no. 13, pp. 14 152–14 158, Jun. 2010.

[28] K. Iga, "Surface-emitting laser-its birth and generation of new optoelectronics field," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1201–1215, Nov./Dec. 2000.

[29] A. Karim, S. Bjorlin, J. Piprek, and J. Bowers, "Long-wavelength vertical-cavity lasers and amplifiers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1244–1253, Nov./Dec. 2000.

[30] C. J. Chang-Hasnain, "Tunable VCSEL," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 978–987, Nov./Dec. 2000.

[31] L. Sun, G. Qin, G. K. Celler, W. Zhou, and Z. Ma, "12-GHz thin-film transistors with transferrable silicon nanomembranes for high-performance massive flexible electronics (Cover Story)," *Small*, vol. 6, no. 22, pp. 2553–2557, Nov. 2010.

[32] Z. Mi and P. Bianucci, "When self-organized In(Ga)As/GaAs quantum dot heterostructures roll up: Emerging devices and applications," *Curr. Opin. Solid State Mater. Sci.*, vol. 16, no. 2, pp. 52–58, Apr. 2012.

[33] W. Huang, X. Yu, P. Froeter, R. Xu, P. M. Ferreira, and X. Li, "On-chip inductors with self-rolled-up SiNx nanomembrane tubes: A novel design platform for extreme miniaturization," *Nano Lett.*, vol. 12, no. 12, pp. 6283–6388, Dec. 2012.

[34] S. Forrest, "The path to ubiquitous and low-cost organic electronic appliances on plastic," *Nature*, vol. 428, no. 6986, pp. 911–918, Apr. 2004.

[35] C. Kagan, D. Mitzi, and C. Dimitrakopoulos, "Organic-inorganic hybrid materials as semiconducting channels in thin-film field-effect transistors," *Science*, vol. 286, no. 5441, pp. 945–947, Oct. 1999.

[36] WTEC, International Assessment of Research and Development in Flexible Hybrid Electronics. [Online]. Available: http://www.wtec.org/flex/

[37] Z. Ma and L. Sun, "Will future RFIC be flexible? (Invited)," in *Proc. IEEE 10th Annu. WAMICON*, Clearwater, FL, USA, 2009, pp. 1–5.

[38] Y. Sun and J. A. Rogers, "Inorganic semiconductors for flexible electronics," *Adv. Mater.*, vol. 19, no. 15, pp. 1897–1916, Aug. 2007.

[39] H. C. Yuan, G. K. Celler, and Z. Ma, "7.8-GHz flexible thin-film transistors on a low-temperature plastic substrate," *J. Appl. Phys.*, vol. 102, no. 3, pp. 034501-1–034501-4, Aug. 2007.

[40] H. Yang, Z. Qiang, H. Pang, Z. Ma, and W. D. Zhou, "Surface-normal fano filters based on transferred silicon nanomembranes on glass substrates," *Electron. Lett.*, vol. 44, no. 14, pp. 858–859, Jul. 2008.

[41] L. Chen, Z. Qiang, H. Yang, H. Pang, Z. Ma, and W. D. Zhou, "Polarization and angular dependent transmissions on transferred nanomembrane Fano filters," *Opt. Exp.*, vol. 17, no. 10, pp. 8396–8406, May 2009.

[42] Z. Qiang, H. Yang, L. Chen, H. Pang, Z. Ma, and W. Zhou, "Fano filters based on transferred silicon nanomembranes on plastic substrates," *Appl. Phys. Lett.*, vol. 93, no. 6, pp. 061106-1–061106-3, Aug. 2008.

[43] W. Zhou and Z. Ma, "Semiconductor nanomembranes for stacked and flexible photonics (Invited)," presented at the Photonics West, San Jose, CA, USA, 2010.

[44] H.-C. Yuan, J. Shin, G. Qin, L. Sun, P. Bhattacharya, M. G. Lagally, G. K. Celler, and Z. Ma, "Flexible photodetectors on plastic substrates by use of printing transferred single-crystal germanium membranes," *Appl. Phys. Lett.*, vol. 94, no. 1, pp. 013102-1–013102-3, Jan. 2009.

[45] W. Yang, H. Yang, G. Qin, Z. Ma, J. Berggren, M. Hammar, R. Soref, and W. Zhou, "Large-area InP-based crystalline nanomembrane flexible photodetectors," *Appl. Phys. Lett.*, vol. 96, no. 12, pp. 121107-1–121107-3, Mar. 2010.

[46] W. Yang, S. Chuwongin, D. Zhao, H. Yang, Z. Ma, and W. Zhou, "Flexible solar cells based on stacked semiconductor nanomembranes on plastic substrates," presented at the Conf. Lasers Electro-Optics (CLEO), San Jose, CA, USA, 2010.

[47] S. Chuwongin, W. Yang, H. Yang, W. D. Zhou, and Z. Ma, "Flexible crystalline InP nanomembrane LED arrays," in *Proc. IEEE Photonics Society Annu. Meet.*, Denver, CO, USA, 2010, pp. 643–644.

[48] X. Xu, H. Subbaraman, A. Hosseini, C. Y. Lin, D. Kwong, and R. T. Chen, "Stamp printing of silicon-nanomembrane-based photonic devices onto flexible substrates with a suspended configuration," *Opt. Lett.*, vol. 37, no. 6, pp. 1020–1022, Mar. 2012.

[49] H. Zhou, J.-H. Seo, D. M. Paskiewicz, Y. Zhu, G. K. Celler, P. Voyles, W. Zhou, M. Lagally, and Z. Ma, "Fast flexible electronics with strined silicon nanomembranes," *Nat. Sci. Rep.*, vol. 3, p. 1291, Feb. 2013.

[50] M. M. Roberts, L. J. Klein, D. E. Savage, K. A. Slinker, M. Friesen, G. Celler, M. A. Eriksson, and M. G. Lagally, "Elastically relaxed free-standing strained-silicon nanomembranes," *Nat. Mater.*, vol. 5, no. 5, pp. 388–393, May 2006.

[51] S. M. Harazim, V. A. B. Quinones, S. Kiravittaya, S. Sanchez, and O. Schmidt, "Lab-in-a-tube: On-chip integration of glass optofluidic ring resonators for label-free sensing applications," *Lab Chip*, vol. 12, no. 15, pp. 2649–2655, Aug. 2012.
[52] F. Li and Z. Mi, "Optically pumped rolled-up InGaAs/GaAs quantum dot microtube lasers," *Opt. Exp.*, vol. 17, no. 22, pp. 19 933–19 939, Oct. 2009.
[53] Z. Liu, J. Wu, W. Duan, M. G. Lagally, and F. Liu, "Electronic phase diagram of single-element silicon 'strain' superlattices," *Phy. Rev. Lett.*, vol. 105, no. 1, pp. 16802-1–16802-4, Jul. 2010.
[54] R. S. Jacobsen, K. N. Andersen, P. I. Borel, J. Fage-Pedersen, L. H. Frandsen, O. Hansen, M. Kristensen, A. V. Lavrinenko, G. Moulin, H. Ou, C. Peucheret, B. T. Zsigri, and A. Bjarklev, "Strained silicon as a new electro-optic material," *Nature*, vol. 441, no. 7090, pp. 199–202, May 2006.
[55] J. F. Liu, X. C. Sun, R. Camacho-Aguilera, L. C. Kimerling, and J. Michel, "Ge-on-Si laser operating at room temperature," *Opt. Lett.*, vol. 35, no. 5, pp. 679–681, Mar. 2010.
[56] C. Boztug, J. Sánchez-Pérez, F. Sudradjat, R. Jacobson, D. Paskiewicz, M. Lagally, and R. Paiella, "Tensilely strained germanium nanomembranes as infrared optical gain media," *Small*, vol. 9, no. 4, pp. 622–630, Feb. 2013.
[57] J. R. Sánchez-Pérez, C. Boztug, F. Chen, F. F. Sudradjat, D. M. Paskiewicz, R. Jacobson, M. G. Lagally, and R. Paiella, "Direct-bandgap light-emitting germanium in tensilely strained nanomembranes," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 108, no. 47, pp. 18 893–18 898, Nov. 2011.
[58] D. Nam, D. Sukhdeo, A. Roy, K. Balram, S. L. Cheng, K. C. Y. Huang, Z. Yuan, M. Brongersma, Y. Nishi, and D. Miller, "Strained germanium thin film membrane on silicon substrate for optoelectronics," *Opt. Exp.*, vol. 19, no. 27, pp. 25 866–25 872, Dec. 2011.
[59] H. Subbaraman, X. Xu, J. Covey, and R. T. Chen, "Efficient light coupling into in-plane semiconductor nanomembrane photonic devices utilizing a sub-wavelength grating coupler," *Opt. Exp.*, vol. 20, no. 18, pp. 20 659–20 665, Aug. 2012.
[60] Y. Zhang, A. Hosseini, J. Ahn, D. N. Kwong, B. Fallahazad, E. Tutuc, and R. T. Chen, "Vertically integrated double-layer on-chip silicon membranes for 1-to-12 waveguide fanouts," *Appl. Phys. Lett.*, vol. 100, no. 18, pp. 181102-1–181102-4, Apr. 2012.
[61] T. Kim, R. H. Kim, and J. A. Rogers, "Microscale inorganic light-emitting diodes on flexible and stretchable substrates," *IEEE Photon. J.*, vol. 4, no. 2, pp. 607–612, Apr. 2012.
[62] T. Kim, Y. H. Jung, J. Song, D. Kim, Y. Li, H. Kim, I. S. Song, J. J. Wierer, H. A. Pao, and Y. Huang, "High-efficiency, microscale gan light-emitting diodes and their thermal properties on unusual substrates," *Small*, vol. 8, no. 11, pp. 1643–1649, Jun. 2012.
[63] R. H. Kim, H. Tao, T. Kim, Y. Zhang, S. Kim, B. Panilaitis, M. Yang, D. H. Kim, Y. H. Jung, and B. H. Kim, "Materials and designs for wirelessly powered implantable light-emitting systems," *Small*, vol. 8, no. 18, pp. 2812–2818, Sep. 2012.