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Semiconductor Photonic Nanocavity on a Paper Substrate

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Photonic integrated circuits (PICs) based on diverse semiconductor materials have been
developed remarkably owing to the progress made in well-established state-of-the-art

1 nano-fabrication techniques.^[1] Given that PICs can provide high bandwidths and a low-
2 loss platform, they are expected to replace their electronic counterparts.^[2] Recently, the
3 environmentally sensitive issue of discarded electronics came to the fore, which resulted
4 in the emergence of green electronics.^[3] Photonic circuits also contain a large percentage
5 of semiconductors, whereas "green photonics", which use eco-friendly materials, have yet
6 to be demonstrated.

7 Here, we propose and demonstrate a semiconductor optical cavity on a paper
8 substrate. One-dimensional photonic crystal nanocavities are transferred onto a paper
9 substrate using a micro-sized stamp. When considered the refractive index of paper at
10 1.55 μm , the simulation result showed that the nanocavity on paper has a Q-factor of
11 48,000. The nanocavity showed lasing action, which is the first observation of a photonic
12 device operating directly on paper. We also observed a wavelength shift of the
13 nanocavity on filter paper when water infiltrated into cellulose fiber, indicating that this
14 device can be utilized as a sensor. The proposed scheme paves the way for eco-friendly
15 and sustainable photonic devices which can reduce the cost of high-tech devices.

1 Developments in electronics over the past few decades have led to more modern
2 technology and have made electronic devices indispensable in our everyday lives.
3 Currently, consumer electronics such as mobile phones, personal computers and tablets
4 are not only purchased by nearly every individual but are often replaced with newly
5 released models. However, these short lifetimes of electronic devices lead to
6 environmental issues, as discarded semiconductors are not degradable and are
7 sometimes toxic.^[3] Green electronics have emerged as an alternative solution, with the
8 goal of providing environmentally friendly electronics through the partial replacement of
9 inorganic materials with biodegradable materials.^[4] Among the range of eco-friendly
10 materials, paper has attracted the most attention because it is abundant in nature,
11 inexpensive and renewable.^[5, 6] Moreover, by replacing the semiconductor substrate with
12 paper, which merely plays a passive role in the assembly and endurance of individual
13 components, the considerable volume of discarded semiconductor materials can be
14 reduced. Furthermore, paper has a great advantage due to certain mechanical
15 characteristics, such as its flexibility, foldability and low weight.^[7-10] Due to these
16 advantages, electronic components on paper have been reported by many research

groups. In detail, electronics on paper substrates have been successfully demonstrated with metal wires, resistors, and batteries.^[9, 11] More recently, paper functioning as an active part in a device, specifically as an insulator, was also demonstrated.^[12] Thus, the wide range of applications of paper-based electronics shows that paper electronics are expected to play a key role in the effort to develop sustainable technologies. Moreover, the lower cost of paper can make state-of-the-art technologies readily available, especially for developing countries.

Electronic devices are expected to reach limitations soon in terms of bandwidth and integrability.^[13, 14] Therefore, photonic devices as a new concept for handling information have attracted much attention by virtue of their ability to control massive amount of data with a compact size at minimized loss levels.^[1, 2, 15] Photonic components such as light sources and optical waveguides have actively been studied in an effort to replace their electronic counterparts, which have been fully developed over the past few decades.^[16] Photonic circuits are expected gradually to replace electronics, leading to future super-computing devices capable of high speeds and low energy consumption

1 levels. In consequence, the commercialization of photonic devices in the near future will
2 also bring about the issue of discarded semiconductors. As the history of electronic
3 devices holds a solution to this issue via the use of biodegradable materials such as
4 paper, this will inspire developers of photonic devices actively to investigate new
5 substrates for photonic components.

6 Here, we propose and demonstrate an optical component consisting of a
7 semiconductor material which works on a biodegradable paper substrate. Two main
8 discussions follow: First, a small optical device should be integrated onto paper while
9 minimizing nonfunctioning regions on the semiconductor. Secondly, the cellulose fibers
10 which constitute paper have a low refractive index such that the optical modes can be
11 efficiently confined in the semiconductor region. In this study, we adopt a transfer-
12 printing technique involving the use of a micro-scale polydimethylsiloxane (PDMS) stamp
13 to transfer an optical nanocavity selectively. A one-dimensional photonic crystal
14 nanobeam cavity made of InGaAsP is used. We numerically show that the optical cavity
15 on paper, which has a refractive index of ~ 1.46 at $1.55\ \mu\text{m}$, has a Q-factor which exceeds

48,000. We experimentally demonstrate that a photonic crystal nanocavity on paper operates as a laser with a threshold power of ~ 0.2 mW, representing the first demonstration of photonic components working directly on a paper substrate to the best of our knowledge. This photonic device is also proven to be capable as a high-sensitivity sensor. Water is automatically transported to a nanobeam structure one centimeter away to change the surrounding refractive indices, resulting in a resonant peak shift of 27.1 nm. A semiconductor photonic crystal on a green material such as paper can lead to the realization of eco-friendly devices and can reduce the device cost to help with the wider use of state-of-the-art devices in developing countries.

Photonic cavities directly integrated with a paper substrate, as shown in the schematic in Figure 1a, can reduce the amount of discarded semiconductor materials by completely replacing the substrates with biodegradable materials. A broad range of paper materials is available, and each type has a different surface roughness and wicking ability.^[17] The inset of Figure 1a shows a scanning electron microscopy (SEM) image of one type of paper, known as glassine paper or weighing paper. In this study, a photonic nanocavity

in a photonic crystal is selected from among the many available types of optical cavities, such as microdisks and micro-ring resonators, as photonic crystal cavities possess a high Q-factor along with a small mode volume.^[18, 19] Specifically, a type of one-dimensional photonic crystal geometry referred to as a photonic crystal nanobeam is utilized due to its high Q-factor with the existence of a substrate and a surrounding high-index material.^[20, 21] One-dimensional photonic crystal nanobeam cavities embedding three layers of InGaAsP quantum wells (QWs) are fabricated in the following sequence to create a freestanding structure, as shown in Figure 1b. The process involves e-beam lithography, Cl₂-assisted Ar-beam milling, polymethylmethacrylate (PMMA) removal using O₂ plasma, and wet etching using a diluted HCl solution.^[20] These semiconductor photonic crystal nanobeams are transfer-printed onto a glassine paper substrate using a PDMS stamp. The micro-patterned PDMS stamp can detach the nanobeam selectively from its original substrate using a precisely controlled xyz micro-stage.^[21] The entire procedure is a dry process without any adhesive materials. The detailed process is explained in Supporting Information Figure S1. In our experiment, nanobeams are successfully transferred not only to glassine paper but also to a piece of filter paper

(Whatman filter paper No.1) to a Post-it note, and to a photo paper. An optical microscope image of the transferred nanobeams on glassine paper is shown in Figure 1c, and a corresponding SEM image is shown in Figure 1d. One of the nanobeams was scanned using atomic force microscopy (AFM), and the 3D-rendered image is shown in Figure 1e. Although the surface of the paper is rough on the millimeter scale, as it consists of entangled cellulose fibers with a size distribution ranging from a few micrometers to millimeters, a single cellulose fiber has a flat surface on the sub-micrometer scale. The nanobeam has a very small footprint of $500\text{ nm} \times 6\text{ }\mu\text{m}$, implying that the device can be placed on a single strand of cellulose fiber such that the nanobeam can exist on a flat surface, as demonstrated in the SEM image in Figure 1d. Though one strand of the cellulose fiber has a rounded surface, a single nanobeam can be conformally attached to cellulose, as shown in the AFM image in Figure 1e.

A finite-different time-domain (FDTD) simulation is used to compute the Q-factor and resonant wavelength of a photonic nanocavity. A schematic representation of a photonic crystal nanobeam on a paper substrate is shown in Figure 2a. It is critical to

1 ensure that a low-refractive-index substrate is used for the photonic structure so as to
2 confine light inside the semiconductor region and thus sustain a high Q-factor. It was
3 found that paper has a relatively low refractive index of 1.46, which is comparable to that
4 of a glass substrate, while the photonic nanobeam has a high refractive index of 3.4. The
5 refractive index of cellulose at a typical communication wavelength ($\lambda=1.55\text{ }\mu\text{m}$) is
6 calculated by means of modified form of Cauchy's approximation with the calculated
7 dispersion coefficient (see Supporting Information).^[22] The photonic crystal nanobeam
8 consists of an array of uniformly sized airholes with the hole-to-hole distances, i.e., the
9 periods, gradually modulated from $0.90a$ to $1.0a$ to form an optical cavity at the center.
10 In that a smaller period has a higher band frequency, the period is shorter at the center
11 and longer at the end of the structure, as shown in Figure 2b. The Gaussian-like
12 attenuation profile can minimize the cavity loss and increase the Q-factor.^[23] With the
13 FDTD method, we can determine that the Q-factor corresponds to 564,000 with a
14 photonic crystal nanobeam without a substrate (free-standing). The Q-factor is reduced
15 to 48,000 when the paper substrate is introduced. This dramatic drop in the Q-factor is

1 due to the breaking of z-axis symmetry. The electric field intensity on the x-y plane and
2 on the x-z plane is shown in Figure 2c and 2d, respectively.

3 In this study, we report the first semiconductor nanocavity laser operating on a
4 paper substrate, which demonstrates that optical components made of semiconductors
5 can maintain their function on cellulose without significant absorption. The nanobeam is
6 optically pumped with a 10 ns pulse width at a period of 1 μ s at room temperature
7 using a 980 nm laser diode. The emitted light is collected by a 50 $\times$ microscope objective
8 lens with a numerical aperture (NA) of 0.45. The lasing operation is observed at a
9 resonant wavelength of 1472.4 nm, as shown in the photoluminescence (PL) spectrum in
10 Figure 3a. There exists another resonant peak at 1470.9 nm. In the inset of Fig. 3b is a
11 lasing-mode image captured by a near infrared (NIR) camera. The polarization-
12 dependence of the laser emission is shown in Figure 3b, which shows that the emitted
13 light is mainly y-polarized with a high polarization extinction ratio of 0.99. We also
14 measured the output power as a function of the peak pump power, as shown in Figure
15 3c. The measured lasing threshold is $\sim$ 0.2 mW. The lasing operation on a paper

1 substrate shows that cellulose fiber does not provide significant absorption near a
2 communication wavelength of 1.55 μm . This brings about a sufficiently high Q-factor for
3 lasing and implies that a paper substrate is an optically feasible substrate. Here, we also
4 tested the lasing operation while increasing the pulse pump duty cycle by increasing the
5 pump pulse width. When the duty cycle exceeds 10 %, no lasing operation is observed
6 due to Joule heating. We took an identical measurement of free-standing nanobeams
7 while increasing the duty cycle to 10 %; the lasing action disappeared in this case when
8 the duty cycle exceeded 6% (see Supporting Information). This result shows that the
9 paper acts as a slightly better heat sink compared to a free-standing nanobeam.

10 Semiconductor optical cavities such as photonic crystals have high Q-factors such
11 that strong light-matter interaction occurs within a small volume.^[24] Therefore, optical
12 cavities can probe small changes in the refractive index of a surrounding medium,
13 showing shifts in the resonant wavelength.^[25, 26] Such an optical sensing technique
14 requires no labeling, indicating that these devices are reusable and non-toxic.^[27] Thus far,
15 sensors using semiconductor materials have been applied as free-standing structures or

onto low-index substrates such as glass. In this work, the nanobeam sensor is initially combined directly with a paper substrate to make use of the advantages of paper.^[28-30] In this experiment, filter paper (Whatman filter paper No.1) is selected from a wide range of paper types, and a wax pattern is fabricated on filter paper, as shown in Figure 4a. A photonic crystal nanobeam is transfer-printed at the one end of the channel (spot B in Figure 4a). Instead of dropping a target liquid material directly onto the photonic nanobeam, we dropped liquid at the other end of the wax-printed channel (spot A in the Figure 4a), as shown in Figure 4b. The filter paper has good wicking ability such that the liquid can flow without any external force exerted on the device. The red water droplet flows through one end to a spot one centimeter away within 30 seconds, as shown in Figure 4c. The water will eventually cover the nanobeam on the cellulose strand. Schematic expressions of this are shown in Figure 4d and 4e. Optical microscope images of spot B are also shown before and after water absorption in Figure 4f and 4g, respectively. Observations through an optical microscope show that the absorbed water veils the paper and the nanobeam surface. The nanobeam image in Figure 4g was captured after the absorbed water partially leaked out. During the PL measurement step,

we used pure distilled water. The PL spectrum of a nanobeam on a paper substrate is denoted by the black circular line in Figure 4h. After the water permeated from spot A to spot B, the nanobeam laser showed a red shift of 27.1 nm due to the increased refractive index at the surrounding medium. Simulation results showing the resonant shift due to water are shown in Figure S3 in the Supporting Information. The wavelength shift in the experiment is comparable to a case in which water covers a nanobeam structure with living airholes, as the oxide layer on the nanobeam prevented water infiltration inside the airholes (see Supporting Information Figure S3).

In conclusion, we introduce and analyze a photonic component on a paper substrate. Photonic nanocavities in a one-dimensional photonic crystal are directly transfer-printed onto paper in an effort to minimize the amount of discarded semiconductor materials. Cellulose, which constitutes paper, has a low refractive index of 1.46 at communication wavelengths, thus allowing a photonic component to confine light inside a structure. To test the operation of the photonic component operation on a paper substrate, we observed lasing action as a typical device performance metric. An

InGaAsP photonic crystal nanobeam was lased at a threshold of 0.2 mW at room temperature. The same device was also shown to be capable as a sensor. In the sensor experiment, the integration of a photonic crystal nanobeam and paper was shown to have great synergy, as photonic crystals have a high figure of merit as a sensor.

Experimental Section

Transfer printing: A micro-sized polydimethylsiloxane stamp ($15\ \mu\text{m} \times 15\ \mu\text{m} \times 40\ \mu\text{m}$) is fabricated using photolithography. The process uses non-specific Van der Waals forces to detach the sample. The semiconductor optical nanocavities are prepared as a free-standing structure so that slight impulse force by the stamp can detach the nanocavities.

FDTD calculations: We use a three-dimensional FDTD method (Lumerical Solutions, Inc.) in Figure 2 and Supporting Information Figure S3. The refractive indices of the semiconductor and paper are set to 3.4 and 1.46, respectively. In the simulation, absorption by materials is not considered.

Supporting Information

Supporting Information is available online from the Wiley Online Library or from the author.

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Figure 1. Transfer-printing of photonic nanocavities on paper. a) Schematic of semiconductor photonic nanocavities on a paper substrate. The inset shows the surface of glassine paper as taken by scanning electron microscopy (SEM). b) A SEM image of fabricated InGaAsP photonic crystal nanobeams. c) An optical image of three nanobeams transfer-printed onto glassine paper. d) SEM image of c). e) An atomic force microscopy (AFM) image of a photonic crystal nanobeam on glassine paper.

Figure 2. FDTD simulation results. a) Schematic of a semiconductor photonic nanocavity laser on a paper substrate with a refractive index of 1.46. b) The Gaussian-modulated period along the x axis from 0.9 a to 1.0 a . The electric field intensity of the photonic crystal nanobeam c) on the x - y plane and d) on the x - z plane.

Figure 3. Optical characterization of a nanobeam laser on paper. a) Photoluminescence spectrum of a photonic crystal nanobeam above a certain threshold. The inset shows the lasing mode captured by a near infrared (NIR) CCD camera. b) Polarization dependence of the nanobeam laser. c) Measured intensity as a function of the input peak pump power.

1 **Figure 4.** Photonic crystal nanocavity on paper as a refractive index sensor. a)
2 photograph of a wax-printed fluid channel on paper. b) Photograph of a liquid droplet
3 (water) with red dye on a wax-printed fluid channel. c) Photograph of a wax-printed
4 paper sample after liquid absorption. Schematic of a nanobeam on filter paper: d) before
5 water absorption and e) after water absorption. Optical microscope image of a
6 nanobeam at spot B, f) before water absorption and g) after the absorbed water partially
7 leaks out. h) Photoluminescence spectrums of a nanocavity with and without water.

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