Light-Emitting Diodes



Transient Light-Emitting Diodes Constructed from Semiconductors and Transparent Conductors that Biodegrade Under Physiological Conditions

Di Lu, Tzu-Li Liu, Jan-Kai Chang, Dongsheng Peng, Yi Zhang, Jiho Shin, Tao Hang, Wubin Bai, Quansan Yang, and John A. Rogers*

Transient forms of electronics, systems that disintegrate, dissolve, resorb, or sublime in a controlled manner after a well-defined operating lifetime, are of interest for applications in hardware secure technologies, temporary biomedical implants, "green" consumer devices and other areas that cannot be addressed with conventional approaches. Broad sets of materials now exist for a range of transient electronic components, including transistors, diodes, antennas, sensors, and even batteries. This work reports the first examples of transient light-emitting diodes (LEDs) that can completely dissolve in aqueous solutions to biologically and environmentally benign end products. Thin films of highly textured ZnO and polycrystalline Mo serve as semiconductors for light generation and conductors for transparent electrodes, respectively. The emitted light spans a range of visible wavelengths, where nanomembranes of monocrystalline silicon can serve as transient filters to yield red, green, and blue LEDs. Detailed characterization of the material chemistries and morphologies of the constituent layers, assessments of their performance properties, and studies of their dissolution processes define the underlying aspects. These results establish an electroluminescent light source technology for unique classes of optoelectronic systems that vanish into benign forms when exposed to aqueous conditions in the environment or in living organisms.

and interconnects, have high chemical stability and/or they pose risks for release of toxic heavy metals after disposal.[1,3-5] The cost for waste management and the potential environmental hazards motivate research into transient, environmentally friendly classes of LEDs that degrade into nontoxic species in natural conditions.^[4,5] In addition, biomedical implants that include LEDs have potential to offer unprecedented opportunities in diagnostic and therapeutic functions such as spectroscopic tracking of key biomarkers,^[6] optogenetic methods for control of neuronal activity^[7–9] and photodynamic therapies for treating certain types of cancer.^[10,11] Permanent implants are often not necessary, nor are they desirable, for temporary medical conditions, where the potential for infection or other complications typically demand secondary extraction surgeries.^[12,13] The additional cost, pain, and risk of hemorrhage^[14] from such surgeries could be eliminated by the use of transient platforms, for which biodegradable LEDs could provide useful levels of functionality currently unavailable from

The increased rates of production and shortened lifecycles of light-emitting diodes (LEDs) in displays and sources for general illumination lead to corresponding increases in concern about the impact of the associated electronic waste on the environment.^[1,2] Many components in commercial LEDs, such as III–V semiconductors, organic emitters, metal electrodes,

Dr. D. Lu, T.-L. Liu, Dr. J.-K. Chang, Prof. D. Peng, Dr. J. Shin, Prof. T. Hang, Dr. W. Bai, Q. Yang, Prof. J. A. Rogers Center for Bio-Integrated Electronics Northwestern University Evanston, IL 60208, USA E-mail: jrogers@northwestern.edu Prof. D. Peng Key Laboratory of Optoelectronic Devices and Systems Shenzhen University Shenzhen 518060, China The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adma.201902739.

DOI: 10.1002/adma.201902739

the existing portfolio of devices in this field.^[12,13]

Recent work in transient electronics defines a set of nontoxic, biodegradable active, and passive materials, ranging from semiconductors and their derivatives (Si, SiO₂, SiN_x, ZnO),^[15–17] to metals (Mg, Zn, Mo, W),^[18] bioinspired organic molecules^[19] and polymers.^[20] In the context of LEDs, partially biodegradable

Prof. Y. Zhang Department of Biomedical, Biological, and Chemical Engineering University of Missouri Columbia, MO 65211, USA Prof. T. Hang State Key Laboratory of Metal Matrix Composites School of Material Science and Engineering Shanghai Jiao Tong University Shanghai 200240, China Dr. W. Bai, Prof. J. A. Rogers Department of Materials Science and Engineering Northwestern University Evanston, IL 60208, USA





Figure 1. Characteristics and hydrolysis behaviors of high-quality ZnO films formed by pulsed laser deposition on monocrystalline silicon substrates. a) Wide range XRD $2\theta-\omega$ scan of a ZnO (200 nm)/Si (111) film showing highly oriented film growth. b) Surface morphology of the same ZnO film. c) Optical images showing the degradation of a ZnO film (200 nm) due to immersion in phosphate buffered saline (PBS) solution (pH = 7.4) at 37 °C and d) ZnO thickness and Zn²⁺ concentration $c(Zn^{2+})$ in the buffer solution as a function of time. The dashed lines are guides to the eye.

riboflavin- and peptide-based organic devices have been reported.^[5,21] Nevertheless, full biodegradability of the two key elements in an LED, namely, a direct bandgap semiconductor to allow recombination of injected electrons and holes for light emission, and a transparent electrode to allow escape of the emitted light, have yet to be demonstrated in a single device for light emission. Here, we demonstrate the construction of a fully transient LED by use of a II-VI semiconductor, ZnO, and an ultrathin (8 nm) transparent electrode of Mo, formed via pulsed laser deposition techniques and standard microfabrication processes. Integrating these materials onto a biodegradable, thin Si substrate with biodegradable insulation layers (SiO₂) and electrical leads (W), yields a device that emits light with a maximum optical power density of 0.7 mW cm⁻² at 9 V, with a blue-violet near-band-edge emission and a broad visible emission likely due to defect states. Addition of biodegradable optical filters based on Si nanomembranes yields LEDs with narrow emission profiles at selected wavelengths throughout the visible range.

Although ZnO is a well-established direct bandgap $(3.3 \text{ eV})^{[22]}$ semiconductor, its light emission capabilities were not experimentally realized until 2004 due to difficulties in growth of high-quality ZnO p–n junctions for hole/electron injection and recombination.^[23] In this work, we use silicon as the "p-type material" for the junction, as a reliable and readily accessible alternative to p-type ZnO. The alignment of the valence bands between properly doped n-type Si ($\approx 10^{18} \text{ cm}^{-3}$) and n-type ZnO allows injection of holes from the Si side.^[24] For the n-type ZnO, we grow highly textured films on monocrystalline silicon substrates by pulsed laser deposition (PLD, details of ZnO growth see the Experimental Section).^[25] PLD is one of a few growth techniques that can produce high-quality ZnO films under a broadly tunable oxygen background pressure $p(O_2)$, to

yield a strong modulation effect on the emission spectrum as well as the conductivity through a controlled density of oxygen vacancies. For example, ZnO grown at high oxygen pressure shows almost pure near-band-edge emission and low conductivity, while that grown at low oxygen pressure shows defect emission as well and with higher conductivity.^[26] Such features allow the growth of conductive ZnO films with both near-bandedge and defect emission, suitable for use in white LEDs. X-ray diffraction (XRD) and atomic force microscopy (AFM) studies reveal the structural and morphological quality of ZnO films grown on Si (111). The XRD $2\theta-\omega$ scan in Figure 1a shows peaks only associated with ZnO (002) and (004), indicating highly (001)-oriented crystal growth. The surface roughness of the film measured by AFM is 1.1 nm (arithmetic roughness R_{a} , Figure 1b). The thicknesses of the ZnO films for the devices reported here are ≈200 nm, as confirmed by profilometry. Identical fabrication processes with ≈300 nm thick ZnO films yield LED devices with similar properties.

Studies of the kinetics of the hydrolysis of ZnO involve immersion of patterned films of ZnO (200 μ m × 200 μ m squares) into a phosphate buffered saline (PBS, pH = 7.4) solution at 37 °C, to simulate conditions comparable to those present in biomedical applications. After 48 h, the ZnO film dissolves in the PBS solution without residue (Figure 1c,d). The data indicate that the rate of dissolution increases with time of immersion (12–36 h), likely correlated to an increased surface roughness (Figure S1, Supporting Information) and associated interface area with the surrounding solution. The average dissolution rate (4 nm h⁻¹) is similar to values reported in a previous study (12 nm h⁻¹ in deionized water).^[17] Previous reports have also identified slightly soluble Zn(OH)₂ as the end product of ZnO hydrolysis,^[17] while we are able to achieve completely soluble Zn²⁺ likely due to the minimal amount of ZnO used here.

ADVANCED SCIENCE NEWS _____

а b 100 Mo (nm) 12 16 Mo R_{sq} (kΩ/sq) 50 % 0.1 0 10 15 400 500 0 5 20 600 700 Metal Thickness (nm) λ (nm) d С 100 W (nm) 4 12 16 ⊢ 50 Northwestern Mo 4 nm W 4 nm 400 500 600 700 λ (nm)

Figure 2. Optical transmission properties and electrical conductivity of thin biodegradable metal films. a) Sheet resistances of thin films of Mo and W. The dashed line is a guide to the eye. b,c) Transmission spectra of Mo (b) and W (c) with different thicknesses. d) Optical image of Mo and W (4 nm) coated a glass plate resting on top of a computer display to illustrate their transparency.

The Zn²⁺ concentration [$c(Zn^{2+})$] in the PBS solution, detected by a selective fluorescent chelating agent zinquin (Experimental Section),^[27] saturates after 48 h to a value that corresponds to complete degradation (\approx 33 ng mL⁻¹, Figure 1d). Such result suggests that the ZnO films directly degrade into Zn²⁺ by hydrolysis (ZnO + H₂O \rightarrow Zn²⁺ + 2OH⁻) instead of forming Zn(OH)₂ precipitates, which agrees with the fact that the saturated $c(Zn^{2+})$ is well below the solubility of Zn(OH)₂ experimentally observed at 25–50 °C around pH 7.4 (3.2–21 µg mL⁻¹, in Zn²⁺).^[28]

Various biodegradable metal thin films can be considered for transient transparent electrodes, where the sheet resistance and optical transmission are key considerations. The sheet resistances R_{sq} of sputtered Mo and W films are 100–1000 Ω (**Figure 2**a), similar to typical transparent conductors such as indium tin oxide at thicknesses of 10–100 nm.^[29] The visible light transmittances *T* of both Mo and W are ~60%, 30%, 20%, and 15% for 4, 8, 12, and 16 nm films, respectively (Figure 2b,c), well below the ~80% transmittance of indium tin oxide.^[29] The transparency of Mo is slightly higher than W, and both metal films show no significant wavelength dependence (Figure 2b,c). Optical images of 4 nm thick transparent Mo and W films deposited on glass are shown in Figure 2d.

Fabrication of fully transient LEDs involve oxygen vacancy doped n-type ZnO(001) films (200 nm, cathode, carrier concentration 1.1×10^{18} cm⁻³, mobility 21.3 cm² V⁻¹s⁻¹) deposited on n-type Si(111) substrates (anode, carrier concentration $\approx 10^{18}$ cm⁻³) by PLD. A patterned layer of SiO₂ (≈ 15 nm) deposited across the ZnO to leave only a 20 µm \times 20 µm opening defines the active area of the device (**Figure 3**a, bottom inset). Depositing a uniform thin film Mo electrode (8 nm) and patterning a comparatively thick layer of W (≈ 100 nm) around the window allows delivery of current through a low resistance path

to the active area. Backside reactive ion etching (RIE) reduces the thickness of the silicon substrate to small values (\approx 12 µm for the example shown here) to facilitate transient behavior on relatively short timescales. The exploded view illustration and the optical image in Figure 3a highlight the device and its structure. Connecting an external DC voltage source to the LED through transient Mg wires and transient conductive pastes^[18] enables light emission (Figure S2, Supporting Information). Nontransient power supplies interfaced to the devices using transient wiring can be used for certain applications bioresorbable medical implants.^[12] Transient wireless harvesting units represent additional options.^[19]

www.advmat.de

The threshold voltage of the ZnO LED is ≈5 V, as observed in the optical power density-current-voltage (L-I-V) curve (Figure 3b) and optical images (Figure S2, Supporting Information), similar to typical ZnO p-n junction LEDs.^[23,30] The intensity of the emitted light is significantly lower (maximum 0.7 mW cm⁻² at 9 V, higher voltage may damage the device) than that of commercial LEDs for displays and optogenetics (0.01–1 W cm⁻²), $^{[7,31]}$ and similar to those used for low-dose applications such as in metronomic photodynamic cancer therapies.^[11] Emission spectra at different activation currents show peaks in the blue-violet, corresponding to the radiative transition across the direct bandgap. This peak suggests that the design reported here allows for injection of holes from the Si valence band to the ZnO valence band and recombination with electrons in the ZnO conduction band.^[24] A wide emission profile across the red-green wavelength range also appears, likely due to defect level transitions (Figure 3c). The peak from 500 to 650 nm can be attributed to oxygen vacancy transitions $(\approx 2.2 \text{ eV})^{[32]}$ while the tail from 650 nm to the infrared likely arises from zinc vacancy transitions (≈1.6 eV).^[33]

This broadband emission feature allows fabrication of red (R), green-yellow (G), and blue-violet (B) LEDs by the addition of transient Fabry-Perot optical filters. The filters reported here use interferences in freestanding monocrystalline silicon nanomembranes with thicknesses of 85, 62, and 42 nm. The optical transmittance spectra of these filters appear in Figure 3d. Integration involves transfer printing these filters onto sheets of biodegradable poly(lactic-co-glycolic acid) (PLGA, $\approx 10 \ \mu m$), followed by placement on top of the LED. The resulting devices selectively allow the transmission of the R, G, and B light as shown in the optical images (Figure 3e). Further RGB color analysis of the images (Figure S3, Supporting Information) reveal that the filtered light always contains a strong red component, which agrees with the high-intensity red tail observed in the emission spectrum (>650 nm, Figure 3c). The biodegradability of the silicon nanomembranes and the PLGA sheets is well established.[13,15,17,18,20]

Immersion of these types of LEDs in PBS solution at 37 °C allows examination of transience at the device level. The various layers dissolve and degrade in a nearly uniform manner (**Figure 4a**). The thickness of the W (80 nm) decreases gradually over a few days by slowly reacting with water, leaving a 40 nm thick residual layer of WO_x after 8 d. This oxide layer dissolves completely in 80–200 d. The complete reaction corresponds to $2W + 2H_2O + 3O_2 \rightarrow 2H_2WO_4$.^[18,34] The layer of Mo (8 nm) decreases in thickness in the first a few hours and completely disappears after 1 d, according to $2MO + 2H_2O + 3O_2 \rightarrow 2M_2WO_4$.







Figure 3. Fully transient ZnO light emitting diodes. a) Exploded view schematic illustration of the LED structure. Bottom inset: a magnified schematic illustration of the structure around the transparent Mo window. Top inset: optical image of a completed LED. Magnified images of the same LED at "on" and "off" states are also shown. b) Optical power density–current–voltage (L-I-V) curve of a representative LED. c) Visible emission spectra of an LED at different operation voltages. d) Transmission spectra of blue-violet (B), green-yellow (G), and red (R) filters formed using silicon nanomembranes. e) Optical images of the nanomembrane filters and filtered light from the LEDs.



www.advancedsciencenews.com





Figure 4. Degradation of transient ZnO LEDs. a) Optical images showing the degradation of a transient LED in PBS solution (pH = 7.4) at 37 °C. Insets: magnified images around the emission window. b) Scanning electron microscopy images showing the degradation of the Si substrate in PBS solution accelerated by heating to 95 °C. c) Thickness of the individual layers in the LED as a function of time at 37 °C. d) Percentage coverage of the ZnO film as a function of time at 37 °C. e) Thickness of the Si substrate as a function of time at 95 °C. The dashed lines are guides to the eye.

 $2H_2MoO_4$.^[18,35] The thickness of the SiO₂ (15 nm) decreases with a nearly constant rate over 8 d, and its complete dissolution is projected to occur in \approx 30 d, according to SiO₂ + 2H₂O \rightarrow Si(OH)₄, Figure 4c.^[13] The degradation rates (25 nm d⁻¹ for W, 8 nm d⁻¹ for Mo, and 0.44 nm d⁻¹ for SiO₂) are comparable to those described in previous reports (50–500 nm d⁻¹ for W and 7–25 nm d⁻¹ for Mo in Hank's solution, 0.01–10 nm d⁻¹ for SiO₂ in aqueous buffer solution).^[16,18]

Residues, defects and thickness variations associated with dissolution of the W and SiO_2 lead to nonuniformities in the dissolution of the ZnO. Specifically, the surrounding solution tends to penetrate through local regions of these overlayers



to dissolve the ZnO in a corresponding spatially dependent manner (Figure S4, Supporting Information). The percentage coverage of the ZnO laver appears in Figure 4d. After 8 d, the ZnO film is completely removed from the substrate. Increasing the temperature of the PBS solution to 95 °C thermally accelerates the dissolution of the Si substrate to allow studies of this process on laboratory timescales. Here, the dissolution rate is 1.2 µm d⁻¹ (Figure 4b,e), consistent with Arrhenius scaling of rates measured at lower temperatures (5 nm d⁻¹ at 37 °C, 67 nm d⁻¹ at 70 °C).^[36] Full degradation of the Si substrate (≈12 µm) under physiological conditions is projected to occur in \approx 5 years. This time can be reduced simply by reducing the thickness. The final degradation products are either essential to life $(Zn^{2+}, MoO_4^{2-})^{[37]}$ or they have low toxicity $[WO_4^{2-},$ $\mathrm{Si}(\mathrm{OH})_4]^{[13,38]}$ to biological systems, and they are therefore also benign to the environment.

In summary, the results reported here serve as the foundations for transient, bio/ecoresorbable LEDs based on ZnO and Si for the semiconducting materials, SiO₂ for the insulating layers, and Mo and W for the conductive films and electrodes. The LEDs emit broadband white light, such that optical filtering with transient silicon nanomembranes allows for operation as R, G, or B devices. These advances add to the larger set of device components available in transient electronic/optoelectronic systems, with options in environmentally friendly and bioresorbable light sources for practical applications. For example, transient LEDs with transient Si waveguides may enable localized spectroscopic evaluation of biochemistry,[39] and the transient LED itself may act as a low-power light source for photodynamic cancer therapy.^[11] Additional work on highquality p-type ZnO films might lead to enhancements in the quantum efficiency and optical power density.^[23] Designing appropriate biodegradable color conversion phosphors or quantum dots instead of light filters might further enhance the quantum yield for improved efficiency by taking advantage of the high-energy blue-violet near-band-edge emission as well as the intense red defect emission.^[40,41]

Experimental Section

ADVANCED SCIENCE NEWS _____

Device Fabrication and Characterization: Single-side-polished n-type Si (111) wafers (phosphorus-doped, resistivity 0.005–0.05 Ω cm, thickness 0.5 mm, MTI Corp.) mechanically thinned from the unpolished side yielded 60 μ m thick substrates. Si wafers with other doping concentrations were also possible for the LED fabrication. The threshold voltages increased with increasing resistivity of the Si. Immersion in buffered oxide etchant ($NH_4F:HF = 10:1$) for 10 min removed the native oxide on the surfaces. The ZnO thin films were grown on the thinned Si (111) by PLD. The system employed a 248 nm KrF excimer laser with a 25 ns pulse duration and was operated at 15 Hz. Zinc oxide was deposited from a dense hot-pressed ZnO target at a laser energy of 200 mJ per pulse. A ≈30% energy loss along the optical train yielded an effective energy at the target of 140 mJ per pulse. The laser pulse was focused to a $\approx 4 \text{ mm}^2$ spot size at the target to yield an effective energy fluence of 3.5 J cm^{-2} . The target was rotated at 13 rpm about its axis to prevent localized heating. The target-substrate separation was fixed at 8 cm. A deposition ambient of 1 mTorr ultrahigh-purity (UHP) oxygen and deposition temperature of 650°C was used.

The ZnO structural quality and surface morphology were characterized by a high-resolution X-ray diffraction system (Cu $K_{\alpha 1}$ emission) and an

AFM in tapping mode, respectively. Carrier concentration and mobility of the ZnO film were determined by a Hall effect measurement system in van der Pauw configuration. Square pads of ZnO were patterned by photolithography using S1813 photoresist (3000 rpm, 30 s) and etching in 5% HCl for 2 s.

The patterned SiO₂, Mo, W layers were fabricated by subsequent photolithography, sputtering at room temperature, and photoresist lift-off with acetone. SiO₂ was sputtered at 200 W under argon partial pressure p(Ar) = 5 mTorr, Mo at 130 W under p(Ar) = 3 mTorr and W at 100 W under p(Ar) = 5 mTorr. The fabricated devices were spin-coated with MicroChem PMMA A11 (1000 rpm, 60 s) and AZ4620 photoresist (2000 rpm, 30 s) double layers to protect the surface, and their thicknesses were reduced from the backside to 12 μ m by using reactive ion etching. The protective layers were removed by acetone. Mg wires (250 μ m imes 250 μ m cross section) obtained by laser-cutting a 250 μ m thick Mg foil provided electrical connections to external power supplies. Degradable conductive wax^[19] bonded these wires to contacts on the LEDs. Optical power of the LED was collected and measured in an integrating sphere implemented with a calibrated Si photodiode sensor using 550 nm average wavelength, and the I-V curve was measured by a semiconductor parameter analyzer. The emission spectra were obtained by using the optics of a laboratory Raman system with an external voltage source. In all experiments, bias was applied on Si and ZnO was grounded.

Fabrication and Characterization of Transparent Electrodes: Mo, W films were sputtered on glass slides and SiO₂ (40 nm)/Si (001) substrates (1 cm \times 1 cm) using the above conditions. The optical transmittance of the transparent electrodes on glass was characterized using a UV-vis spectrometer. The sheet resistance of the transparent electrodes on Si substrates was measured by a semiconductor parameter analyzer in four-point van der Pauw configuration.

Fabrication and Characterization of Si Nanomembrane Filters: The top silicon on silicon-on-insulator (SOI) wafers (device layer 200 nm) were thinned to 85, 62, and 42 nm by reactive ion etching, and patterned into 200 μ m × 200 μ m or 1 mm × 1 mm squares by photolithography and reactive ion etching. The wafers were then immersed in 49% HF to etch the underlying SiO₂ layer to yield freestanding Si nanomembranes that were then transfer-printed onto sheets of poly(lactic-*co*-glycolic acid). The optical transmittance spectra of 1 mm × 1 mm filters were characterized by a UV-vis spectrometer.

Degradation: To monitor $c(Zn^{2+})$ in PBS solutions as a function of time, ZnO films (1.35 mm × 1.35 mm × 200 nm, equivalent to the amount of ZnO in one transient LED) were immersed in 50 mL PBS at 37 °C. 2 mL solutions at 0, 2, 3, 6 d were collected and centrifuged under 3500 × g for 10 min to separate possible insoluble particles and solution. 0.1 mL 10 × 10⁻⁶ M Zinquin ethyl ester (Adipogen, 0.5×10^{-3} M in dimethyl sulfoxide) and 0.5 mL 2-propanol were added to each solution as a fluorescent indicator and a homogenizer, and the fluorescence was quantified in a spectrofluorimeter (activation at 370 nm, emission 400–600 nm). The degradation of the LED was induced by immersion in 50 mL PBS solution at 37 or 95 °C. The PBS solution was refreshed every 24 h. The thickness of each layer in the LED was measured by either an AFM or a profilometer at the edge, or a scanning electron microscope in cross-section configuration at an acceleration voltage 15 kV.

Supporting Information

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

Acknowledgements

This work utilized Northwestern University Micro/Nano Fabrication Facility (NUFAB), which was partially supported by Soft and Hybrid





Nanotechnology Experimental (SHyNE) Resource (NSF ECCS-1542205), the Materials Research Science and Engineering Center (NSF DMR-1720139), the State of Illinois, and Northwestern University, and the Center for Bio-Integrated Electronics at the Simpson/Querrey Institute. This work made use of the EPIC and SPID facility of Northwestern University's NUANCE Center, which had received support from the Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource (NSF ECCS-1542205); the MRSEC program (NSF DMR-1720139) at the Materials Research Center; the International Institute for Nanotechnology (IIN); the Keck Foundation; and the State of Illinois, through the IIN. This work made use of the Pulsed Laser Deposition Shared Facility at the Materials Research Center at Northwestern University supported by the National Science Foundation MRSEC program (DMR-1720139) and the Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource (NSF ECCS-1542205).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

biomedical implants, degradation, light-emitting diodes, transient devices, waste management

- Received: April 29, 2019
- Revised: August 4, 2019
- Published online: September 6, 2019
- P. Kiddee, R. Naidu, M. H. Wong, Waste Manage. 2013, 33, 1237.
- [2] P. Tanskanen, Acta Mater. 2013, 61, 1001.
- [3] S. R. Lim, D. Kang, O. A. Ogunseitan, J. M. Schoenung, Environ. Sci. Technol. 2011, 45, 320.
- [4] M. J. Tan, C. Owh, P. L. Chee, A. K. K. Kyaw, D. Kai, X. J. Loh, J. Mater. Chem. C 2016, 4, 5531.
- [5] N. Jürgensen, M. Ackermann, T. Marszalek, J. Zimmermann, A. J. Morfa, W. Pisula, U. H. F. Bunz, F. Hinkel, G. Hernandez-Sosa, ACS Sustainable Chem. Eng. 2017, 5, 5368.
- [6] S. H. Yun, S. J. J. Kwok, Nat. Biomed. Eng. 2017, 1, 0008.
- [7] T. I. Kim, J. G. McCall, Y. H. Jung, X. Huang, E. R. Siuda, Y. H. Li, J. Z. Song, Y. M. Song, H. A. Pao, R. H. Kim, C. F. Lu, S. D. Lee, I. S. Song, G. Shin, R. Al-Hasani, S. Kim, M. P. Tan, Y. G. Huang, F. G. Omenetto, J. A. Rogers, M. R. Bruchas, *Science* **2013**, *340*, 211.
- [8] S. I. Park, D. S. Brenner, G. Shin, C. D. Morgan, B. A. Copits, H. U. Chung, M. Y. Pullen, K. N. Noh, S. Davidson, S. J. Oh, J. Yoon, K. I. Jang, V. K. Samineni, M. Norman, J. G. Grajales-Reyes, S. K. Vogt, S. S. Sundaram, K. M. Wilson, J. S. Ha, R. Xu, T. Pan, T. I. Kim, Y. Huang, M. C. Montana, J. P. Golden, M. R. Bruchas, R. W. t. Gereau, J. A. Rogers, *Nat. Biotechnol.* **2015**, *33*, 1280.
- [9] K. L. Montgomery, A. J. Yeh, J. S. Ho, V. Tsao, S. Mohan Iyer, L. Grosenick, E. A. Ferenczi, Y. Tanabe, K. Deisseroth, S. L. Delp, A. S. Poon, *Nat. Methods* **2015**, *12*, 969.
- [10] P. Agostinis, K. Berg, K. A. Cengel, T. H. Foster, A. W. Girotti, S. O. Gollnick, S. M. Hahn, M. R. Hamblin, A. Juzeniene, D. Kessel, M. Korbelik, J. Moan, P. Mroz, D. Nowis, J. Piette, B. C. Wilson, J. Golab, CA - Cancer J. Clin. 2011, 61, 250.
- [11] K. Yamagishi, I. Kirino, I. Takahashi, H. Amano, S. Takeoka, Y. Morimoto, T. Fujie, *Nat. Biomed. Eng.* **2019**, *3*, 27.



- [12] S. K. Kang, R. K. Murphy, S. W. Hwang, S. M. Lee, D. V. Harburg, N. A. Krueger, J. Shin, P. Gamble, H. Cheng, S. Yu, Z. Liu, J. G. McCall, M. Stephen, H. Ying, J. Kim, G. Park, R. C. Webb, C. H. Lee, S. Chung, D. S. Wie, A. D. Gujar, B. Vemulapalli, A. H. Kim, K. M. Lee, J. Cheng, Y. Huang, S. H. Lee, P. V. Braun, W. Z. Ray, J. A. Rogers, *Nature* **2016**, *530*, 71.
- [13] K. J. Yu, D. Kuzum, S. W. Hwang, B. H. Kim, H. Juul, N. H. Kim, S. M. Won, K. Chiang, M. Trumpis, A. G. Richardson, H. Cheng, H. Fang, M. Thomson, H. Bink, D. Talos, K. J. Seo, H. N. Lee, S. K. Kang, J. H. Kim, J. Y. Lee, Y. Huang, F. E. Jensen, M. A. Dichter, T. H. Lucas, J. Viventi, B. Litt, J. A. Rogers, *Nat. Mater.* **2016**, *15*, 782.
- [14] J. K. Liu, H. Soliman, A. Machado, M. Deogaonkar, A. R. Rezai, J. Neurosurg. 2012, 116, 525.
- [15] S. W. Hwang, G. Park, C. Edwards, E. A. Corbin, S. K. Kang, H. Y. Cheng, J. K. Song, J. H. Kim, S. Yu, J. Ng, J. E. Lee, J. Kim, C. Yee, B. Bhaduri, Y. Su, F. G. Omennetto, Y. G. Huang, R. Bashir, L. Goddard, G. Popescu, K. M. Lee, J. A. Rogers, ACS Nano 2014, 8, 5843.
- [16] S.-K. Kang, S.-W. Hwang, H. Cheng, S. Yu, B. H. Kim, J.-H. Kim, Y. Huang, J. A. Rogers, Adv. Funct. Mater. 2014, 24, 4427.
- [17] C. Dagdeviren, S. W. Hwang, Y. Su, S. Kim, H. Cheng, O. Gur, R. Haney, F. G. Omenetto, Y. Huang, J. A. Rogers, *Small* **2013**, *9*, 3398.
- [18] L. Yin, H. Cheng, S. Mao, R. Haasch, Y. Liu, X. Xie, S.-W. Hwang, H. Jain, S.-K. Kang, Y. Su, R. Li, Y. Huang, J. A. Rogers, *Adv. Funct. Mater.* **2014**, *24*, 645.
- [19] S. M. Won, J. Koo, K. E. Crawford, A. D. Mickle, Y. Xue, S. Min, L. A. McIlvried, Y. Yan, S. B. Kim, S. M. Lee, B. H. Kim, H. Jang, M. R. MacEwan, Y. Huang, R. W. Gereau, J. A. Rogers, *Adv. Funct. Mater.* **2018**, *28*, 1801819.
- [20] L. S. Nair, C. T. Laurencin, Prog. Polym. Sci. 2007, 32, 762.
- [21] S. Khanra, T. Cipriano, T. Lam, T. A. White, E. E. Fileti, W. A. Alves, S. Guha, Adv. Mater. Interfaces 2015, 2, 1500265.
- [22] Ü. Özgür, Y. I. Alivov, C. Liu, A. Teke, M. A. Reshchikov, S. Doğan, V. Avrutin, S. J. Cho, H. Morkoç, J. Appl. Phys. 2005, 98, 041301.
- [23] A. Tsukazaki, A. Ohtomo, T. Onuma, M. Ohtani, T. Makino, M. Sumiya, K. Ohtani, S. F. Chichibu, S. Fuke, Y. Segawa, H. Ohno, H. Koinuma, M. Kawasaki, *Nat. Mater.* **2004**, *4*, 42.
- [24] S. T. Tan, X. W. Sun, J. L. Zhao, S. Iwan, Z. H. Cen, T. P. Chen, J. D. Ye, G. Q. Lo, D. L. Kwong, K. L. Teo, *Appl. Phys. Lett.* **2008**, *93*, 013506.
- [25] W. R. Liu, Y. H. Li, W. F. Hsieh, C. H. Hsu, W. C. Lee, Y. J. Lee, M. Hong, J. Kwo, Cryst. Growth Des. 2009, 9, 239.
- [26] C.-F. Yu, C.-W. Sung, S.-H. Chen, S.-J. Sun, Appl. Surf. Sci. 2009, 256, 792.
- [27] A. B. Nowakowski, D. H. Petering, Inorg. Chem. 2011, 50, 10124.
- [28] R. A. Reichle, K. G. McCurdy, L. G. Hepler, Can. J. Chem. 1975, 53, 3841.
- [29] D. B. Fraser, H. D. Cook, J. Electrochem. Soc. 1972, 119, 1368.
- [30] A. Tsukazaki, M. Kubota, A. Ohtomo, T. Onuma, K. Ohtani, H. Ohno, S. F. Chichibu, M. Kawasaki, *Jpn. J. Appl. Phys.* 2005, 44, L643.
- [31] P. Destruel, P. Jolinat, I. Seguy, G. Ablart, J. Farenc, *IEEE Ind. Appl. Mag.* 2008, 14, 12.
- [32] P. Camarda, F. Messina, L. Vaccaro, S. Agnello, G. Buscarino, R. Schneider, R. Popescu, D. Gerthsen, R. Lorenzi, F. M. Gelardi, M. Cannas, Phys. Chem. Chem. Phys. 2016, 18, 16237.
- [33] X. J. Wang, L. S. Vlasenko, S. J. Pearton, W. M. Chen, I. A. Buyanova, *J. Phys. D: Appl. Phys.* **2009**, *42*, 175411.
- [34] W. A. Badawy, F. M. Al-Kharafi, Electrochim. Acta 1998, 44, 693.
- [35] A. Shah Idil, N. Donaldson, J. Neural Eng. 2018, 15, 021006.

ADVANCED SCIENCE NEWS

www.advancedsciencenews.com



- [36] Y. K. Lee, K. J. Yu, E. Song, A. Barati Farimani, F. Vitale, Z. Xie, Y. Yoon, Y. Kim, A. Richardson, H. Luan, Y. Wu, X. Xie, T. H. Lucas, K. Crawford, Y. Mei, X. Feng, Y. Huang, B. Litt, N. R. Aluru, L. Yin, J. A. Rogers, ACS Nano 2017, 11, 12562.
- [37] P. Trumbo, A. A. Yates, S. Schlicker, M. Poos, J. Am. Diet. Assoc. 2001, 101, 294.
- [38] J. L. Domingo, Biol. Trace Elem. Res. 2002, 88, 097.
- [39] W. Bai, H. Yang, Y. Ma, H. Chen, J. Shin, Y. Liu, Q. Yang, I. Kandela, Z. Liu, S. K. Kang, C. Wei, C. R. Haney, A. Brikha, X. Ge, X. Feng, P. V. Braun, Y. Huang, W. Zhou, J. A. Rogers, *Adv. Mater.* **2018**, *30*, 1801584.
- [40] J. McKittrick, L. E. Shea-Rohwer, D. J. Green, J. Am. Ceram. Soc. 2014, 97, 1327.
- [41] P. Hartmann, P. Pachler, E. L. Payrer, S. Tasch, *Proc. SPIE* **2009**, *7231*, 72310X.