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Programmable polyphasic stimulation with bioresorbable phototransistors

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A wireless stimulation platform that is based on a bioresorbable phototransistor can provide precise, programmable and multi-site electrotherapy through tissue-penetrating optical modulation.

Wireless electrical stimulation devices can provide electrotherapy without the need for wired connections that penetrate multiple tissue layers[1–3]. By eliminating leads, such wireless technologies can offer minimally invasive implantation and can reduce the risks associated with infection and mechanical failure[4–6]. However, most existing wireless stimulators generate only simple electrical pulses, as their output waveforms are tightly constrained by signals from the external power sources. This limits therapeutic precision and versatility[6,7]. In particular, in many clinical applications, including cardiac pacing and neuromodulation, the stimulation signal waveform influences both efficacy and safety. Biphasic or polyphasic waveforms, in which the current alternates direction over time, can, for instance, reduce tissue damage by balancing injected charge and improve energy efficiency compared with simple monophasic pulses. These considerations are particularly important for bioresorbable electronics designed for temporary therapies[8], where controlled stimulation is essential within limited operational lifetimes. Writing in *Nature Electronics*, John Rogers and colleagues now report a bioresorbable wireless electronic platform that can generate programmable polyphasic stimulation waveforms using light-controlled silicon devices[9].

The approach is based on a bioresorbable silicon phototransistor that functions as an optically gated switch embedded in the stimulation circuit (Fig. 1a). When illuminated with near-infrared light, which can penetrate biological tissue, the phototransistor generates a photocurrent that can dynamically control current flow and polarity at selected circuit nodes. By modulating the intensity and timing of the incident light, the system can decouple waveform generation from the incoming wireless power, allowing the electrical outputs to be shaped precisely.

The bioresorbable silicon phototransistors are constructed using conventional semiconductor processes, including dopant-defined junction engineering in thin silicon layers, followed by transfer onto biodegradable polymer substrates. The devices incorporate p–n–p junctions for efficient carrier transport under illumination (Fig. 1b). When exposed to near-infrared light, they generate a photocurrent, and switch from a high-resistance state (megaohm scale) to a low-resistance state (kiloohm scale), allowing dynamic modulation of current flow. Importantly, the devices offer fast switching speeds, with response times of tens of microseconds, which are sufficient to support the temporal control required for polyphasic waveform generation. They can also maintain stable operation across physiological temperatures and exhibit predictable degradation behaviour over time, consistent with the bioresorbable property of the whole platform (Fig. 1c).

Using the phototransistor platform, the team — who are based at institutions in the USA, the Republic of Korea and Singapore — demonstrate light-controlled generation of a range of stimulation waveforms within a wireless system. Wireless power is first converted into a quasi-direct-current signal, which is then dynamically modulated by near-infrared illumination. By modulating the intensity and timing of light, the system produces different monophasic waveforms with tunable amplitude, duration and frequency, and enables coordinated multisite stimulation with programmable latency (Fig. 1d). Furthermore, cross-coupled phototransistor configurations can provide rapid switching of current polarity, allowing charge-balanced polyphasic waveforms and high-frequency alternating-current outputs in the kilohertz range to be generated. These results highlight, in particular, that optical control can provide a flexible and independent means to program complex stimulation waveforms in wireless bioelectronic systems (Fig. 1d).

The capabilities of this programmable waveform control are validated in vivo through cardiac pacing in a canine model. Using light-controlled stimulation, the system supports multiple pacing modes, including single-site and dual-site pacing, as well as temporally coordinated activation of different cardiac chambers (Fig. 1e,f). By independently modulating optical inputs, the device can control inter-site latency, allowing simultaneous biventricular pacing and sequential atrioventricular pacing that more closely mimic physiological conduction patterns. While monophasic and biphasic stimulation produce comparable electrical activation of the heart, biphasic pulses achieve pacing at substantially lower voltage thresholds, highlighting improved energy efficiency and reduced stimulation burden.

The versatility of the programmable waveform control is further demonstrated through neuromodulation of the phrenic neuromuscular system in rodent models. The device can provide both activation and inhibition within the same platform, and by increasing the stimulation frequency of monophasic pulses, it can precisely control diaphragm muscle activity, producing transitions from single-twitch responses to sustained contractions (Fig. 1g). By contrast, high-frequency polyphasic waveforms in the kilohertz range induce a reversible nerve conduction block, effectively suppressing diaphragm motion. These functions are achieved with stable operation and minimal adverse tissue response, highlighting the feasibility of transient, bioresorbable systems for neuromuscular modulation.

This wireless bioelectronic stimulation system can generate waveforms decoupled from external power delivery and can be controlled with high temporal precision. By integrating optically gated silicon electronics made of bioresorbable materials, it offers minimally invasive and transient implantation, and a level of functional flexibility that extends beyond conventional wireless systems. Optical control in deep and heterogeneous tissues will though require strategies to mitigate

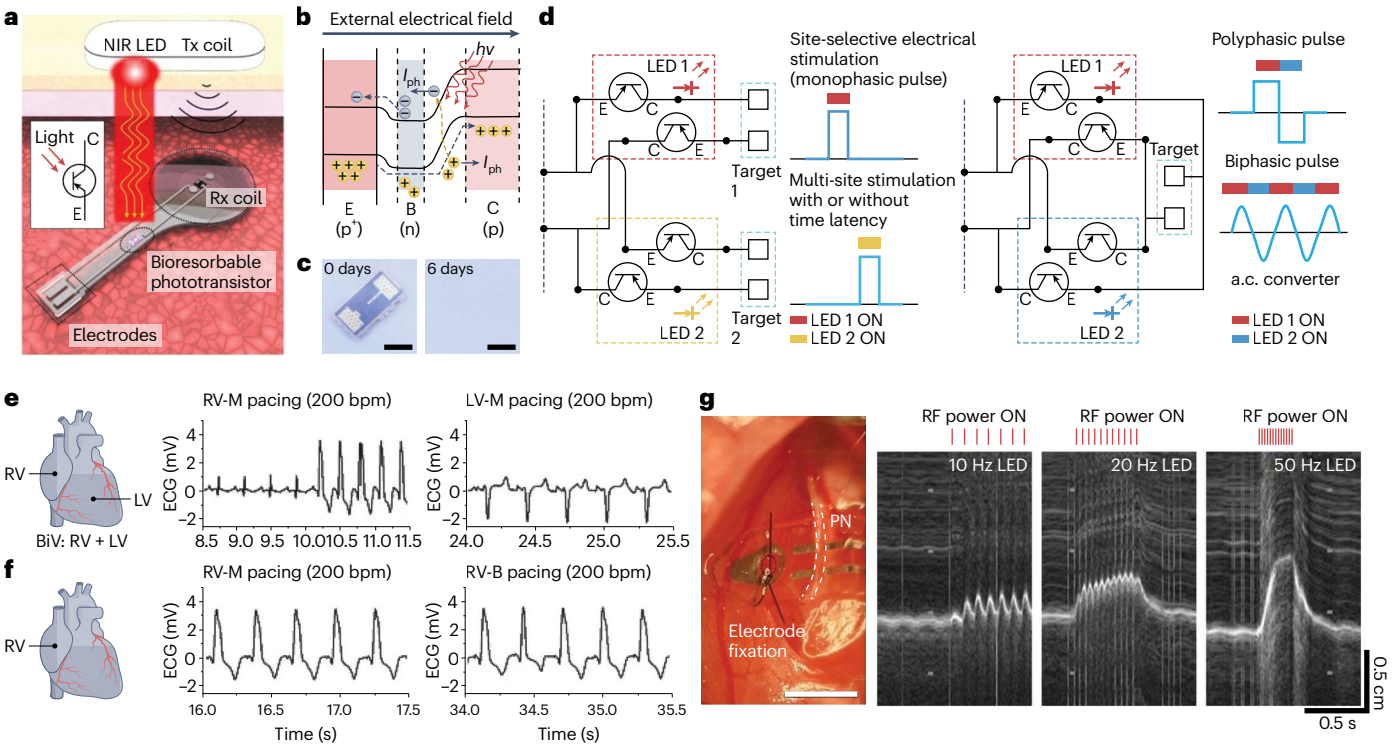

Fig. 1 | A wirelessly powered bioresorbable silicon electronic system for programmable polyphasic electrical stimulation. a, Schematic of the device architecture and operating principle. The system integrates a receiving coil (Rx) for wireless power harvesting and a bioresorbable phototransistor for optical control, driven by a skin-interfaced unit that includes a near-infrared (NIR) light-emitting diode (LED) and a transmitting coil (Tx). C, collector; E, emitter. **b**, Energy band diagram of the bioresorbable phototransistor, consisting of p^+-doped emitter (E), n-doped base (B) and p-doped collector (C) regions. I_{ph}, photocurrent. **c**, Time-sequenced dissolution of a printed bioresorbable phototransistor on a bioresorbable substrate in phosphate-buffered saline (pH 7.4) at an elevated temperature (95 °C). **d**, Circuit configurations for multi-site stimulation and programmable generation of polyphasic waveforms. **e**, Representative electrocardiogram (ECG) recordings during dual-site cardiac pacing with monophasic pulses, including right ventricle (RV), left ventricle (LV) and biventricular (BiV) modes. RV-M, RV-monophasic; LV-M, LV-monophasic. **f**, ECG recordings during single-site cardiac pacing using biphasic and polyphasic stimulation waveforms. RV-B, RV-biphasic. **g**, Bipolar cuff electrode implanted on the phrenic nerve (PN) for diaphragm muscle stimulation. Ultrasound images with frequency-dependent diaphragm responses, transitioning from twitching to sustained excursion as the LED stimulation frequency increases from 10 Hz to 50 Hz. RF, radiofrequency. Scale bars, 1 mm (**c**,**g**). Figure adapted from ref. 9, Springer Nature Limited.

scattering and crosstalk, potentially through wavelength-selective activation or improved device sensitivity. Further miniaturization and integration with alternative wireless power schemes could also eliminate the need for receiver coils and enable fully distributed systems. In addition, combining programmable stimulation with multimodal sensing and on-device processing could lead to the development of closed-loop bioelectronic therapies that dynamically adapt to physiological states. With such advances, the approach could ultimately provide intelligent, transient and wirelessly programmable medical devices for precision electrotherapy.

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Competing interests

The authors declare no competing interests