Multiplexed Complementary Signal Transmission for a Self-Regulating Artificial Nervous System

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Abstract

Neuromorphic engineering has emerged as a promising research field that can enable efficient and sophisticated signal transmission by mimicking the biological nervous system. This paper presents an artificial nervous system capable of facile self-regulation via multiplexed complementary signals. Based on the tunable nature of the Schottky barrier of a complementary signal integration circuit, a pair of complementary signals was successfully integrated to realize efficient signal transmission. As a proof of concept, a feedback-based blood glucose level control system was constructed by incorporating a glucose/insulin sensor, a complementary signal integration circuit, an artificial synapse, and an artificial neuron circuit. Certain amounts of glucose and insulin in the initial state were detected by each sensor and reflected as positive and negative amplitudes of the multiplexed presynaptic pulses, respectively. Subsequently, the pulses were converted to postsynaptic current, which triggered the injection of glucose or insulin in a way that confined the glucose level to a desirable range. The proposed artificial nervous system demonstrates the notable potential of practical advances in complementary control engineering.

Introduction

The recent decade has witnessed significant advancements in the development of neuromorphic systems capable of energy-efficient signal transmission by replicating the functions of biological nervous systems\(^1\)\(^{-}\)\(^{12}\). In recent years, several researchers have attempted to use neuromorphic engineering to realize bio-functional complementation\(^1\(^3\)\(^{-}\)\(^{28}\). For example, Lee's group designed an artificial afferent nervous system that can be directly connected to the motor neurons of the leg of a discoid cockroach\(^22\). The authors demonstrated that the artificial nervous system can successfully control the leg actuation through the application of external stimuli. Although such studies provided great scope on the bioelectronics, most of the systems involved only a potentiation-driven response system, and the construction of an artificial nervous system capable of concurrently modulating a pair of complementary signals (i.e., potentiation and depression) remains to be realized. In particular, complementary signals allow the development of more sophisticated and efficient control/regulation systems. The excellence of complementary signal control/regulation systems can be found in the human body: The transmission of complementary signals through separate channels of the sympathetic nervous system (SNS) and parasympathetic nervous system (PSNS) enables the secretion of antagonistic hormones to maintain homeostasis\(^29\)\(^{-}\)\(^{31}\). However, the involvement of multiple signal transmission channels is a critical drawback in realizing artificial complementary signal control systems owing to the high circuit complexity and inefficiency. Although multi-input artificial nervous systems have been reported\(^32\)\(^{-}\)\(^{35}\), these systems primarily relied on a multiple presynaptic terminal-structure yielding a fundamental limit in figuring out the issues. Therefore, a novel input architecture that can process a pair of complementary input signals and is compatible with artificial stimulus-response systems is of significance to establish an efficient control system.
In this manuscript, we developed an artificial complementary nervous system (ACNS) capable of facile and sophisticated self-regulation based on the highly efficient signal transmission realized by integrating two complementary signals into a single integrated or multiplexed presynaptic signal. The system was constructed by incorporating sensors, a signal integration circuit (SIC), an artificial synapse (AS), and an artificial neuron circuit (ANC) to regulate the blood glucose level essential to maintaining homeostasis. The glucose and insulin levels were converted into electrical signals by sensors connected to the SIC. The two complementary signals were reflected as positive and negative amplitudes of the presynaptic pulse voltage through Schottky barrier (SB) modulation of two Schottky barrier transistors (SBT) connected in series. The resulting multiplexed voltage pulse was transmitted to the AS to generate postsynaptic current (PSC), which is an indicator of the glucose level. Finally, the injection of glucose and insulin was controlled according to the level of the PSC through the neuron circuit via two regulation methods by varying the electrical components of the circuit.

**Result**

**Operating principle of ACNS for complementary control.**

Figure 1a depicts a biological control system based on the complementary signals of SNS/PSNS. The combination of these systems results in complementary stimuli delivered to organs, such as promotion-inhibition and dilation-contraction. Although a biological control system can effectively control the internal environment of the human body through complementary signals, the presence of SNS and PSNS necessitates two independent signal transmission channels, which leads to a high system complexity. In contrast, the proposed ACNS combines the two complementary signals into an integrated signal before it reaches the associated organs, thereby simplifying the transmission system to realize efficient signal transmission, as shown in Fig. 1b.

The operating characteristics of the SIC are of significance in integrating the two complementary signals: Changes in individual signal types can be discerned to reflect each signal in the form of positive and negative amplitudes of the pulses. Figure 1c shows a circuit diagram of the SIC that integrates two complementary signals into voltage pulses. The circuit contains two SBTs connected in series in opposite directions. When the complementary input signals ($V_{G1}$ and $V_{G2}$) to be integrated enter the gate of each SBT, an AC supply pulse applied to the drain ($V_{IN}$) is converted to an asymmetric AC output pulse, the positive and negative amplitudes of which are adjusted according to each input signal. The varying amplitude the two signs of the asymmetric AC can be attributed to the tunable diode behavior of the SBTs. The upper panel of Fig. 1d and Supplementary Fig. 1 show schematic structure and optical microscopy image of two SBTs connected in series, respectively. Each SBT has a graphene/n-type semiconductor/metal heterojunction (Supplementary Fig. 2). Such this structure allows the modulation of the SB, as shown in the lower panel of Fig. 1d. In the forward bias mode, the injection of electrons from the metal into the semiconductor is not affected because the work function change of the metal owing to $V_G$ is negligible. In contrast, in the reverse mode, the electron injection can be adjusted based on $V_G$ because the SB at the graphene/semiconductor interface can be either raised or lowered by applying...
negative or positive $V_G$, respectively\textsuperscript{36–39}. The voltage polarity of the SBTs determines the sign of the output current that can be adjusted, as shown in Fig. 1e. In the case of SBT1 (left panel of Fig. 1e), the reverse mode occurs in the negative drain voltage ($V_D$) region. Thus, the positive component of the AC supply pulse yields an output with a constant and high-level positive amplitude, whereas the negative supply component results in $V_G$-dependent negative output pulses. In the case of SBT2 (middle panel of Fig. 1e), the bias condition is reversed: The positive component of the AC supply pulse solely contributes to the positive amplitude of the asymmetric AC pulse, which varies according to $V_G$. When these two SBTs are connected in series (right panel of Fig. 1e), the SBT with the higher resistance determines the amplitude of the output pulse for a given AC supply pulse. As a result, the negative and positive amplitudes of the resulting asymmetric AC output pulse can be modulated only through $V_{G1}$ and $V_{G2}$, respectively.

Figure 1f shows the operational diagram of regulation of blood glucose level by the ACNS. First, the glucose and insulin sensors detect each target substance to convert it into an electrical signal. Subsequently, each signal is integrated to voltage pulses including the information of both the glucose and insulin by SIC. Next, the integrated signal enters the AS, which potentiates and depresses the PSC according to the positive and negative amplitudes of the input signal, respectively. When the level of PSC exceeds the set standard, a logical decision is made to suppress the change in the PSC by the ANC. Consequently, a negative feedback is achieved by transmitting the signal to the actuators that inject glucose or insulin to maintain the glucose level in a desirable range.

**Electrical properties of single SBT and integration of complementary signals by a complementary input interface.**

Figure 2a shows the cross-section and top-view schematic of a single SBT. First, an indium-tin-oxide (ITO) drain electrode and indium-gallium-zinc-oxide (IGZO) channel were sputtered onto a heavily-doped Si/SiO$_2$ substrate. Subsequently, the monolayer graphene was transferred and patterned onto the IGZO channel layer to form the SB between the layers (Supplementary Fig. 3 and 4). Figure 2b and 2c show transfer curves of the SBT under reverse $V_D$ ranging from +0.1 V to +1.0 V in 0.1 V increments and forward $V_D$ ranging from -0.1 V to -1.0 V in -0.1 V increments, respectively (also see the band diagram and output curve are presented in supplementary Fig. S5 and S6, respectively). In the reverse bias mode, the maximum on-off current ratio of 156 was observed when $V_D$ was +0.2 V. However, in the forward bias mode, the on-off current ratio did not exceed 20 under the same $V_D$ range (Supplementary Fig. 7). The rectification ratio, which is defined as the ratio of the forward current to the reverse current at $V_G = 0$ V and 40 V as a function of $V_D$ is plotted in Fig. 2d and Supplementary Fig. 8. When $V_G = 0$ V, the highest rectification ratio was observed at $V_D = 0.4$ V while the ratio approximately converged to 1 under $V_G = 40$ V. For an SBT that exhibits a high rectification ratio, the contribution of the forward mode SBT to the overall output current of the system in which two SBTs in forward and reverse modes are connected in series is negligible. Because the forward mode current of the adopted SBT does not overwhelm the reverse mode current, it is necessary to design the system to ensure that the difference between the
forward and reverse mode currents is maximized. Therefore, $V_0 = 0.4 \text{ V}$, which corresponds to the maximum rectification ratio, was selected as the amplitude of the AC supply pulse of the SIC.

Figure 2e shows the circuit diagram of the complementary input interface, which consists of a glucose sensor, an insulin sensor, and a SIC that incorporates the electric signals from the two sensors. Transistor-type sensors are fabricated for detecting the glucose/insulin level. IGZO was used as a benchmark sensing channel despite its lack of selectivity because the current level can be varied by several orders according to the amounts of glucose or insulin solutions (Supplementary Fig. 9 and 10). The high on-off current ratio of transistor-type sensors allows three glucose/insulin levels to be distinguished. The amounts of glucose and insulin detected by each sensor are first converted to the corresponding $I_{\text{sensor}}$, as shown in the left panel of Fig. 2f. States “0”, “1”, and “2” denote the number of glucose or insulin doses dropped on each sensor, respectively. Next, $I_{\text{sensor}}$ was converted to a voltage signal via a voltage divider followed by voltage amplification. By selecting the proper reference resistance and voltage gain of the amplifier, it is possible to adjust $I_{\text{sensor}}$ to the intended voltage level. In the considered case, states “0”, “1”, and “2” correspond to approximately 0 V, 20 V, and 40 V, respectively, as shown in the right panel of Fig. 2f. Finally, the amplified voltage was applied to the gate of each SBT connected in series in opposite directions while the AC supply voltage, with an amplitude of 0.4 V and frequency of 2 Hz, was applied to the drain of the SBT. During the positive amplitude phase, the SBTs connected to the glucose and insulin sensors were in the reverse and forward modes, respectively. Therefore, the amplitude of the positive composition of the integrated output voltage ($V_{IO}$) pulse was determined by $V_{G1}$ of the SBT connected to the glucose sensor (i.e., the state of glucose). Likewise, the negative composition of the $V_{IO}$ pulse was regulated by the state of insulin. As a proof of concept, the $V_{IO}$ pulse according to the states of glucose and insulin were measured, as shown in Fig. 2g. As the glucose and insulin state increased, the amplitude of the positive and negative components of the $V_{IO}$ pulse increased, respectively, and the state of each substance independently contributed to the amplitude of the $V_{IO}$ pulse.

**Synaptic behavior of AS under integrated pulses.**

In order to regulate the levels of glucose and insulin within a desirable range, it is necessary to first understand the synaptic behavior of the AS induced by the $V_{IO}$ pulse input. Figure 3a depicts the structural schematic of the AS and $V_{IO}$ entering the AS. For the fabrication of the AS, a poly(3-hexylthiophene) (P3HT) and an ion-gel were patterned onto the substrate with Au electrode patterns (Supplementary Fig. 11). Detailed working mechanism of the P3HT/ion-gel AS is as follows: Negative $V_{IO}$ pulses drive the penetration of $[\text{PF}_6]$ anions in the ion-gel into the free volume of the P3HT channel layer and facilitate the doping of the P3HT channel with the anions to increase the PSC. Although the penetrated anions gradually diffuse out from the channel in the absence of the negative $V_{IO}$ pulses, the residual anions in the P3HT prevent a drastic reduction in the PSC, resulting in retentive current characteristics. Furthermore, the penetrated $[\text{PF}_6]$ ions are extracted by positive $V_{IO}$ pulses, and current retention occurs during the absence of $V_{IO}$. Such retentive characteristics of the P3HT/ion-gel layer results
in the synaptic behavior. Figure 3b shows the normalized EPSC and IPSC of the P3HT/ion-gel AS. $V_{io}$ pulses with magnitude from +1 V to +3 V and a width of 40 ms were applied to the ion-gel, and clear EPSC and IPSC responses are observed at a $V_D$ of 0.5 V. Moreover, the AS exhibited reliable long-term potentiation (Fig. 3c) as well as long-term depression behaviors (Fig. 3d). Long-term plasticity due to the retentive ion movement in the P3HT channel was observed up to 50 consecutive pulses, and the changes in the PSC became larger as the pulse magnitude increased.

Based on the fundamental synaptic performance discussed in the previous sections, the PSC change of the P3HT/ion-gel AS by $V_{io}$ pulses was clarified, as shown in Fig. 3e. Prior to applying $V_{io}$ pulses having both positive and negative peak components, the current potentiation by negative pulses with a magnitude of -3 V ($V_{0.3}$) was investigated. As shown in the first panel (black line), gradual PSC increase was observed. Next, the synaptic device subjected to 30 $V_{0.3}$ pulses in advance was exposed to continuous $V_{io}$ pulses, with the magnitude of the positive peak component set as +1 V (red line), +2 V (blue line), and +3 V (green line), and the magnitude of the negative peak component set as -3 V (denoted as $V_{1.3}$, $V_{2.3}$, and $V_{3.3}$, respectively). Compared to $V_{0.3}$, $V_{1.3}$ pulses mitigated the increase in PSC, as indicated by the gray shaded region. In the case of $V_{2.3}$, the PSC decreased from the initial state but maintained a certain current level even when the number of pulses increased. The application of $V_{3.3}$ further decreased the PSC level, reaching nearly zero after nine pulses. Additional experimental results regarding the PSC changes under positive peak components of 0.5 V, 1.5 V, and 2.5 V along with 0 V, 1 V, 2 V, and 3 V are shown in Supplementary Fig. 12. Supplementary Fig. 13 shows the derivative of PSC with respect to the number of pulses. When the number of pulses is sufficiently large and the positive peak component is less than 1 V, the derivative was positive; above 2 V, the value was close to zero. Figure 3f indicates the level of normalized PSC according to the magnitude of the positive peak component. As the depression voltage increased from 0 V to 3 V, the PSC after 30 pulses decreased from 2.81 to $9.4 \times 10^{-3}$. These results indicate that the PSC behavior can be controlled by modulating the positive and negative amplitudes of the $V_{io}$ pulses.

To construct a glucose level-regulating system, a Schmitt-trigger-based ANC that provides feedback regarding the glucose and insulin levels was designed. The ANC consists of four electrical parts: i) a resistor-capacitor delay and a non-inverting amplifier that reduces the intensity of the spike component of the synaptic output voltage ($V_{SO}$, ANC-entering voltage converted from PSC) and amplifies the mitigated $V_{SO}$ (i.e., $V_{RC}$), respectively; ii) a Schmitt trigger that outputs the voltages ($V_{SCH}$) for the $V_{RC}$ according to two set thresholds of $V_{UT}$ and $V_{LT}$; iii) a differentiator that converts the square wave of $V_{SCH}$ into a pulse wave ($V_{DIFF}$); and iv) a PNP and NPN bipolar-junction transistor (BJT) that selectively transfers negative or positive pulses (ANC output voltage, $V_{NO}$). These $V_{NO}$ signals induce an injection of glucose and insulin to adjust the glucose level.

Schmitt-trigger-based ANC for glucose-regulating systems.
Since the number and signs of the output pulses depend on the number of Schmitt triggers and the type of BJT, a variety of glucose-level-regulating systems can be implemented by varying these two electrical parameters. Figure 4a shows the simplified circuit diagram of a double-negative spike generation ANC having two Schmitt triggers with different reference voltages ($V_{\text{REF}}$) and a PNP BJT. Utilization of two Schmitt triggers connected in parallel allows three distinct levels of $V_{\text{SCH}}$ to be implemented, thereby yielding double $V_{\text{DIFF}}$ spikes. Moreover, the PNP BJT selectively passes only negative pulses. The concept of the double-negative spike generation mode glucose-level-regulating system is demonstrated in Fig. 4b, which shows the output voltages obtained after traversing each electrical component. As the input, triangular pulses ($V_{\text{Amp}} = 10 \text{ mV}, f = 0.2 \text{ Hz}$) were applied with a supply voltage of ±10 V and $V_{\text{REF}}$ of 4.5 V and 6.5 V. The two pairs of thresholds set according to the Schmitt triggers were $V_{\text{UT}} = 6.5 \text{ V}, V_{\text{LT}} = 2.5 \text{ V}$ and $V_{\text{UT}} = 8.5 \text{ V}, V_{\text{LT}} = 4.5 \text{ V}$ for the double $V_{\text{DIFF}}$ spike. $V_{\text{SCH}}$ exhibits an upshift and downshift when $V_{\text{RC}}$ coincides with $V_{\text{UT}}$ and $V_{\text{LT}}$, yielding a negative and positive pulse, respectively; this phenomenon is followed by the filtering of the positive pulses by the PNP BJT. In this manner, double-negative $V_{\text{NO}}$ spikes capable of inducing a steeper increase in the glucose level could be generated. In addition to the double-negative spike generation ANC, a complementary spike generation mode glucose-level-regulating system was designed by replacing the pair of Schmitt-triggers with a single one and adding an NPN BJT. The operation principle of this system is identical to that of the abovementioned system, except for the $V_{\text{DIFF}}$ spike generation and pulse filtering being performed by the BJT, as shown in the simplified circuit diagram of the complementary spike generation ANC (Fig. 4c and 4d). By using one Schmitt-trigger ($V_{\text{UT}} = 7.5 \text{ V}, V_{\text{LT}} = 3.5 \text{ V}$) and both types of BJT, a single $V_{\text{DIFF}}$ spike in both positive and negative can be obtained. The detailed circuit diagrams of the ANCs are shown in the supporting information (Supplementary Fig. 14 and 15). The advantage of this system is that both glucose and insulin injection can be facilitated in a manner that prevents a radical change in the glucose level.

**Glucose-level-regulating systems controlled by integrated signals.**

Finally, glucose-level-regulating negative feedback loops were constructed by incorporating the functions of the sensor, SIC, AS, and ANC. Two types of glucose-level-regulating feedback loops, characterized by the abovementioned ANC, were demonstrated: a double insulin injection feedback loop, and an insulin-glucose injection feedback loop. Figure 5a shows the logical algorithm of the double insulin injection feedback loop. Unless $V_{\text{RC}}$ exceeds $V_{\text{UT1}}$, no feedback regarding the glucose level is required. When $V_{\text{RC}}$ reaches the first upper threshold ($V_{\text{UT1}}$), which corresponds to an abnormal increase in the glucose level, the ANC outputs a negative pulse to promote insulin injection. After the first injection, $V_{\text{RC}}$ can either remain in the range below $V_{\text{UT1}}$ or further increase to reach the second threshold ($V_{\text{UT2}}$). The former case indicates that the amount of injected insulin is sufficient to stabilize the glucose level. In the latter case, additional insulin is injected to induce a stronger suppression of glucose level increase, leading to glucose level stabilization. Figure 5b exemplifies the former case in which $V_{\text{RC}}$ with an initial glucose state of 1 changes according to the generated $V_{\text{NO}}$. When the increasing $V_{\text{RC}}$ exceeded $V_{\text{UT1}}$, one dose of insulin was injected, and no additional injection is performed. The latter case with an initial glucose state...
of 2 is shown in Fig. 5c. $V_{NO}$ generated by the two thresholds effectively suppressed the rapid increase in $V_{RC}$. The logical algorithm of the insulin-glucose injection feedback loop is shown in Fig. 5d. When $V_{RC}$ approaches $V_{UT}$ or $V_{LT}$ and crosses each threshold, the injection of insulin and glucose, respectively, is implemented to suppress the corresponding change. The regulation of $V_{RC}$ by $V_{UT}$ and $V_{LT}$ is demonstrated in Fig. 5e, successfully confining the level of $V_{RC}$ to within the intended voltage range.

**Discussion**

We designed a complementary control-based self-regulating ANS by adopting a barrier-tunable SBT. To demonstrate the feasibility of the system, a blood glucose level regulation system was constructed by incorporating glucose/insulin sensors, SIC, AS, and ANC. The complementary signals received by each sensor modulate the corresponding SB to be multiplexed into the positive and negative amplitudes of a single presynaptic signal. Next, the signal was transmitted to the AS to generate a PSC, which indicates the blood glucose level that reflects the demultiplexed contributions from each complementary signal. Finally, the ANC, which could be designed to have multiple modes, regulated the blood glucose level by deciding whether glucose and/or insulin injection must be implemented according to the PSC level. The proposed system capable of complementary control and represents a pathway to enhance the sophistication and efficiency of artificial nervous systems.

**Methods**

**Device fabrication.** To fabricate the single SBT and SIC, a 30-nm-thick ITO layer was deposited and patterned as a gate electrode onto a glass substrate conducting radio frequency magnetron sputtering and conventional PR photolithography process (AZ 5214E). After PR patterning, the ITO was chemically etched (35–37 vol% hydrochloric) and sintered in the furnace in ambient conditions (600 °C, 30 min). A 100-nm-thick SiO$_2$ layer was deposited onto the ITO patterned glass substrate via the conventional sol-gel method to form the gate dielectric layer. ITO and IGZO were then deposited and patterned using the same processes as those of the gate electrode to form the metal contact and n-type semiconductor layer, respectively. The IGZO layer was annealed at 300 °C for 2 hr in the furnace and patterned through chemical etching with 3 vol% LCE-12 solution (Cyantek Co). Next, monolayer graphene, grown by conventional chemical vapor deposition, was transferred using the polymeric supporting layer of poly(methyl methacrylate) and patterned via photolithography and subsequent reactive ion etching (RIE). The glucose/insulin sensor was fabricated using ITO source/drain electrodes and an IGZO semiconducting channel. The patterning PR blocking layer was formed to avoid direct contact of the chemicals with the ITO electrodes. To fabricate the AS, a P3HT solution with a concentration of 9 mg/mL in chloroform was prepared with stirring at 50 °C for 6 hr. The prepared P3HT solution was then spin-coated onto the Au-prepatterned glass substrate (1500 rpm and 1 min) and dried overnight under an Ar condition. The deposited P3HT layer was patterned via the same process with graphene. Subsequently, an ion-gel precursor solution composed of poly(ethylene glycol) diacrylate (PEGDA), 2-hydroxy-2-methylpropiophenone (HOMPP) and 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIM][PF$_6$])
ionic liquid with a weight ratio of 2:1:22 was drop-casted onto the Au/P3HT patterned substrate. UV irradiation was conducted to pattern the ion-gel layer through photo-initiated crosslinking.

**ANC and injection system implementation.** The ANCs were composed with of CMOS-based commercial components: an operational amplifier (UA741CP, Texas Instruments), PNP and NPN BJTs (KSB1151YSTU, ON Semiconductor and TTC004BQ, Toshiba, respectively), resistors, and capacitors. The injection system of glucose and insulin solutions was implemented using a linear actuator (HJA301, Richmat).

**Characterization.** The quality of graphene was analyzed through Raman spectroscopy (Alpha300M, Witec). The electrical properties of the single SBT, SIC, glucose/insulin sensor, and AS were evaluated using a Keithley 4200A-SCS and vacuum probe station system. The real-time output signals of ANC components were measured using a digital phosphor oscilloscope (DPO3052, Tektronix).

**Data availability**

All data generated or analyzed during this study are included in this published article (and its Supplementary Information files)

**Declarations**

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**Author contributions**

J.H.C. initiated the research, designed all the experiments. Y.J.C. and D.G.R. carried out most of the experimental work and data analysis. Y.J.C. conducted the fabrication and analysis of the device. D.G.R. desinged and fabricated the ANC for the artificial nervous system. Y.Y.C., and S.K. synthesised and characterized the graphene. S.B.C., H.S.L., and D.H.K. assisted the data analysis. All authors discussed the results and contributed to write the paper.

**Competing interests**

The authors declare no competing interests.

**References**


**Figures**
Figure 1

Operating principle of ACNS for complementary control. a Schematic of complementary SNS/PSNS-based biological antagonistic regulation system. b Schematic of ACNS that uses integrated complementary signals. c Schematic circuit diagram of SIC based on SBTs connected in series in opposite directions. d Schematic cross-sectional structure of SIC and its band diagram at the forward and reverse bias conditions. e VG-dependent output characteristics of an individual SBT and SIC. f Operational diagram of glucose level-regulation system via ACNS.
Figure 2

Electrical properties of single SBT and integration of complementary signals by a complementary input interface. a Schematic structure of a graphene/IGZO SBT. b-c Transfer characteristics of an SBT under b under reverse and c forward bias conditions. d Rectification ratio (|IF|/|IR|) of an SBT as a function of VD at VG = 0 V and 40 V. e Schematic circuit diagram of a complementary input interface composed of a glucose sensor, an insulin sensor, and an SIC. f Isensor, VG1, and VG2 as a function of the glucose and insulin states. g VIO under various glucose and insulin states.
Figure 3

Synaptic behavior of AS under integrated pulses. a Schematic structure of P3HT/ion-gel AS. b Normalized EPSC and IPSC of AS under various VIO pulses. c Long-term plasticity behavior of AS with VIO = -2.5 to -3.5 V. d Long-term depression behavior with VIO = +1.0 to +3.0 V. e PSC of AS according to the negative amplitude of the integrated pulses (V0,3, V1,3, V2,3 and V3,3) after pre-potentiation with 30 negative pulses (VIO = -3 V, W = 40 ms). f Normalized PSC as a function of the positive amplitude of pulses after 30 integrated pulses.

Figure 4

Schmitt-trigger-based ANC for glucose-regulating systems. a Schematic circuit diagram of double-negative spike generation ANC. b Resulting output signals of double-negative spike generation ANC at
each electrical component with triangular VSO (VAmp = 10 mV, f = 0.2 Hz). c Schematic circuit diagram of the complementary spike generation ANC. d Resulting output signals of the complementary spike generation ANC at each electrical component with triangular Vin (VAmp = 10 mV, f = 0.2 Hz).

Figure 5

Glucose-level-regulating systems controlled by integrated signals. a Logical algorithm of glucose-level regulation system using double-negative spike generation ANC. Real-time VRC and VNO changes in the double-negative spike generation ANC under an initial glucose state of b 1 and c 2. d Logical algorithm of glucose-level regulation system using complementary spike generation ANC. Real-time VRC and VNO changes in the complementary spike generation ANC under an initial glucose state of e 1 and f 2.
Supplementary Files

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