# Supporting Information

## Vertical 0.6-Volt Sub-10-nm Oxide-homojunction Transistor Gated by Silk Fibroin/Sodium Alginate Crosslinking Hydrogel for Pain-sensitization Enhancement Emulation

**Jingya Su, Yanran Li, Dingdong Xie, and Jie Jiang***
Hunan Key Laboratory of Nanophotonics and Devices, Hunan Key Laboratory of Super Microstructure and Ultrafast Process, School of Physics and Electronics, Central South University, Changsha, Hunan 410083, China
E-mail: jiangjie@csu.edu.cn

## Experimental Section:

***Preparation of SF and SA solutions:*** For the SF solution, firstly, silkworm cocoons were cutting into pieces, and boiled in $Na_2CO_3$ (0.02 M) solution for 30 min to remove the sericin for three times. Secondly, rinsed the silk fibers with deionized water (DI water) to eliminate the sericin and $Na_2CO_3$, and then dried at 100 $^oC$ for 8 h. Thirdly, the dried silk fibers were dissolved in lithium bromide (LiBr) solution(9.3 M) at 60 $^oC$ for 5 h. Finally, the solution which contained the LiBr and dissolved silk fiber were dialyzed by DI water for 3 days. Then the 4 wt% SF solution is prepared and stored at 4 $^oC$. For the SA solution, the SA powders were dissolved in water solution, and then the 4 wt% SA solution was obtained after 3 days.

***Preparation of SF/SA hybrid solution:*** Firstly, to obtain the different ratio of the hybrid solution, SF solution and SA solution were prepared at the same concentration of 4 wt%. Secondly, different volume ratios of the two solutions were controlled strictly along the beaker with the same concentration. After several attempts, we choose the SF solution: SA solution= 1:2 as the best ratio scheme for the final device fabrication. Thirdly, the fixed ratio of SF/SA hybrid solution was mixed by rotating at 36 $^oC$ for 8 minutes. Finally, the hybrid solution was centrifuged at 9000 rpm for 40 minutes to obtain pure hybrid solution.

***Fabrication of vertical ITO transistor:*** Firstly, the SA/SF hybrid solution was drop-cast onto the FTO-coated glass substrate and dried at 36 $^oC$ for 8 h, then the

SF/SA membrane was obtained. Subsequently, the comb-like bottom source electrode, channel layer, and drain electrode were deposited onto the SSH electrolyte via RF magnetron sputtering with the ITO target (90 wt% $In_2O_3$ and 10 wt% $SnO_2$). The sputtering conditions including working power, chamber pressure and Ar flow rate are consistent during sputtering source electrode and drain electrode (50 W, 0.65 Pa, and 15 sccm, respectively). As for the deposition of ITO channel layer, it keeps the same working power and chamber pressure, and was sputtered in an $Ar/O_2$ (10/7 sccm) mixed-gas environment.

***Characterizations of SF Membrane, SA Membrane, SSH, and ITO Films:***

The FTIR spectrum of SF Membrane, SA Membrane, SSH was measured using NICOLET 6700 FTIR equipment. The thickness information and surface characterization of ITO were performed using AFM equipment (Nanoman VS+Multimode, Veeco). Scanning electron microscopy (SEM) images and energy-dispersive X-ray spectroscopy (EDS) are used to characterize SF Membrane, SA Membrane, SSH.

***Electrical and Photoelectronic Measurements:***

The electric performances and biosynaptic characteristics of the vertical ITO transistor were conducted using a Keithley 4200 Semiconductor Characterization System. Optical signals were supplied with a fiber coupled laser module with a wavelength of 360 nm (UV-F-360nm-19031653), 405 nm (MDL-III-405 nm-18082986).

# Supplementary Figures

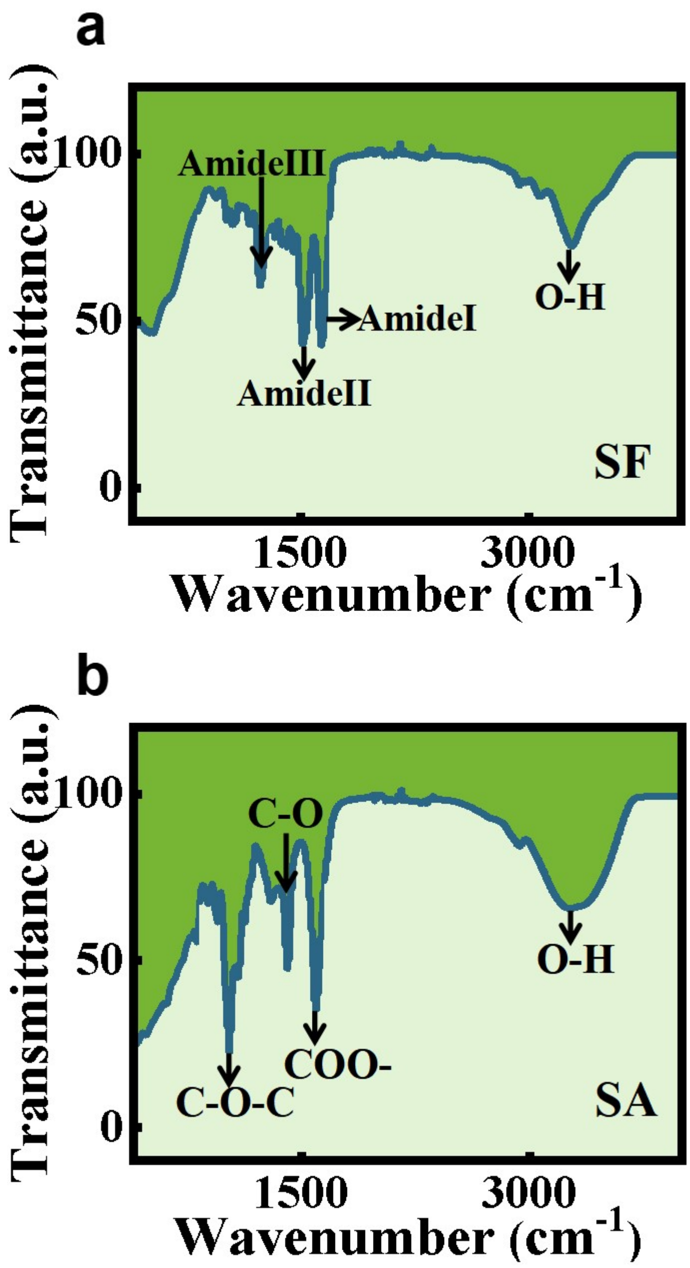



**Fig. S1** FTIR spectra to characterize the mainly functional group. (a) SF membrane. (b) SA membrane.

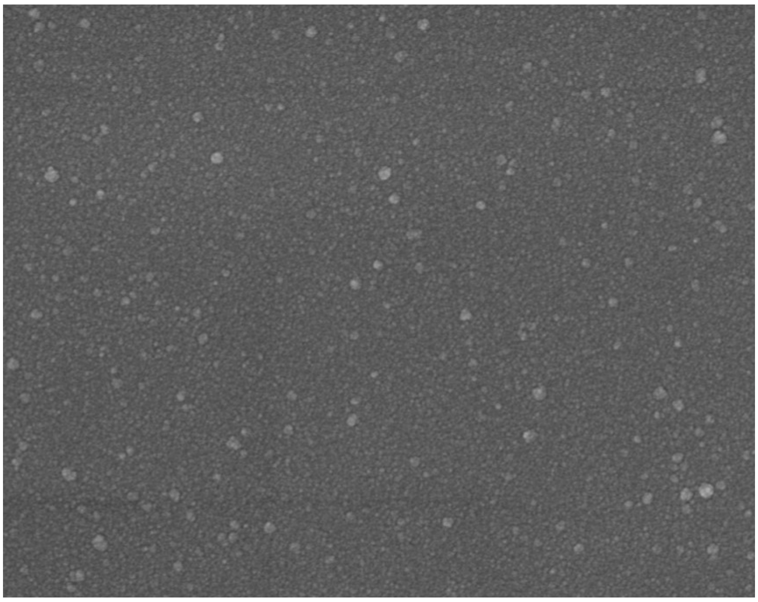


**Fig. S2** The top-view scanning electron microscope (SEM) image of ITO drain electrode.

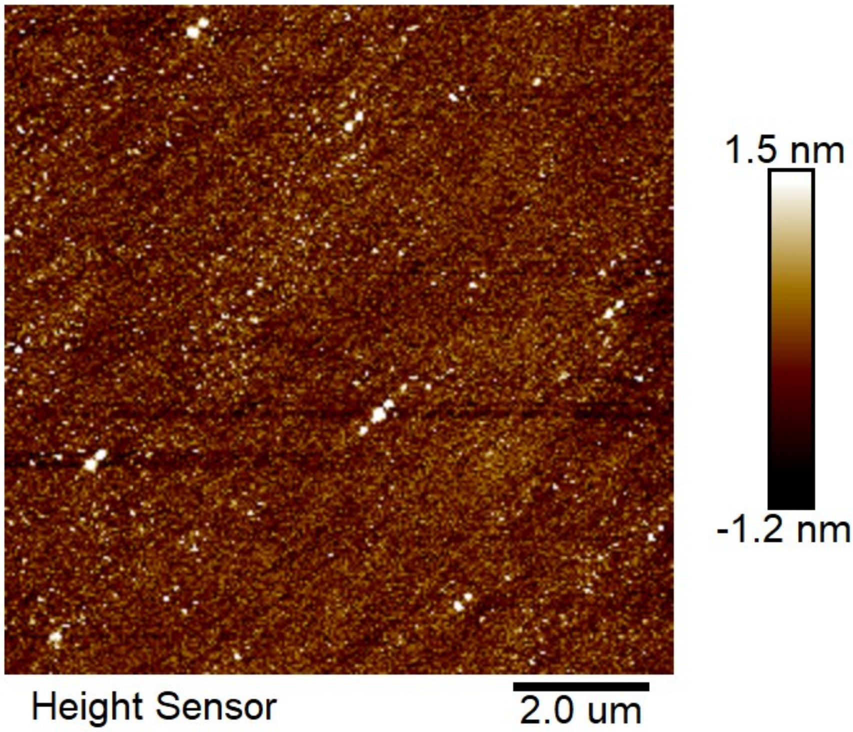



**Fig. S3** The ITO channel morphology was measured through AFM measurement. The root mean square roughness of this film is estimated to be 3.4 nm.

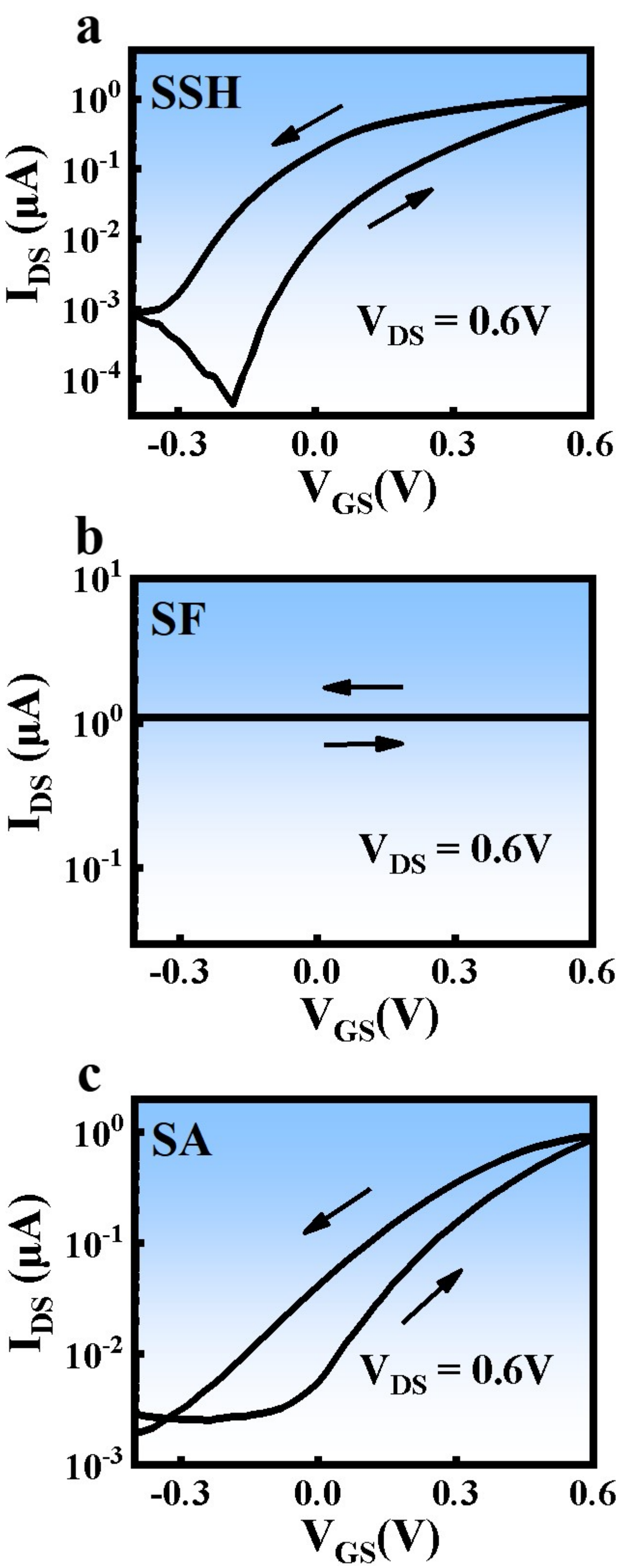



**Fig. S4** Transfer curve of vertical ITO transistors with different gate dielectric: (a) SSH. (b) SF. (c) SA.

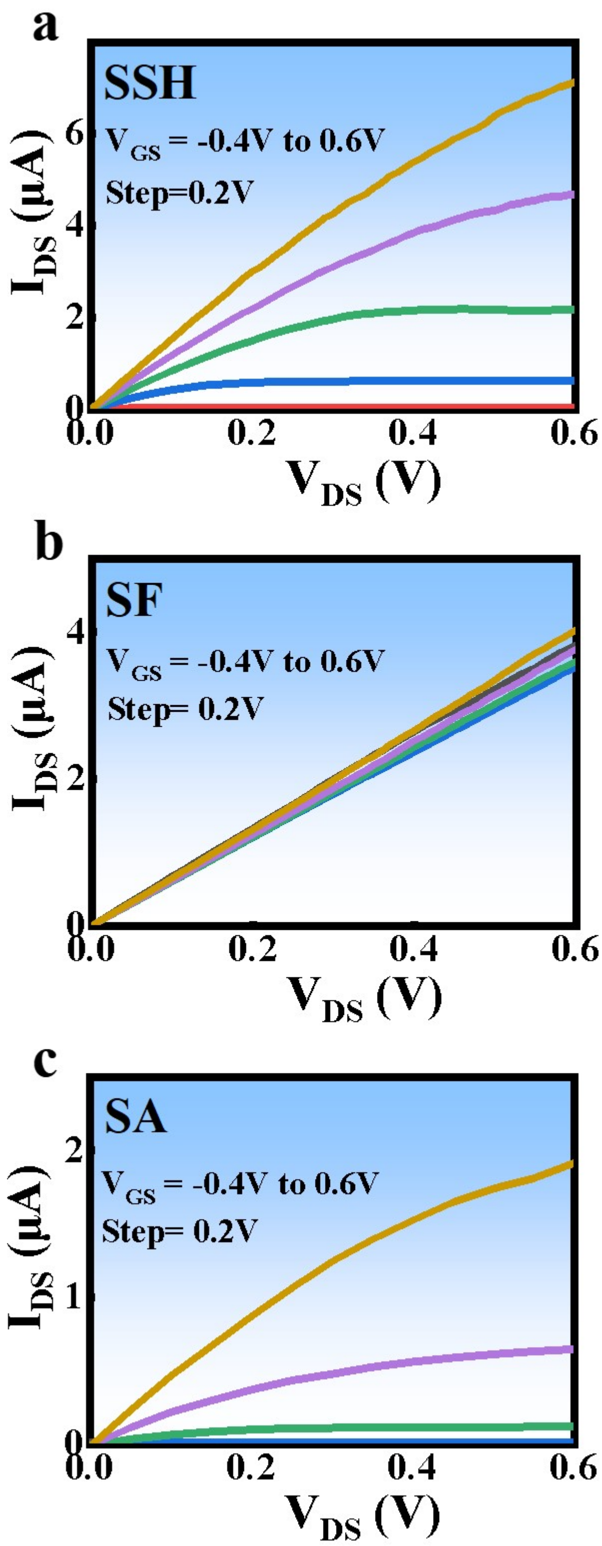



**Fig. S5** Output characteristics of vertical ITO transistors with different gate dielectric: (a) SSH. (b) SF. (c) SA.

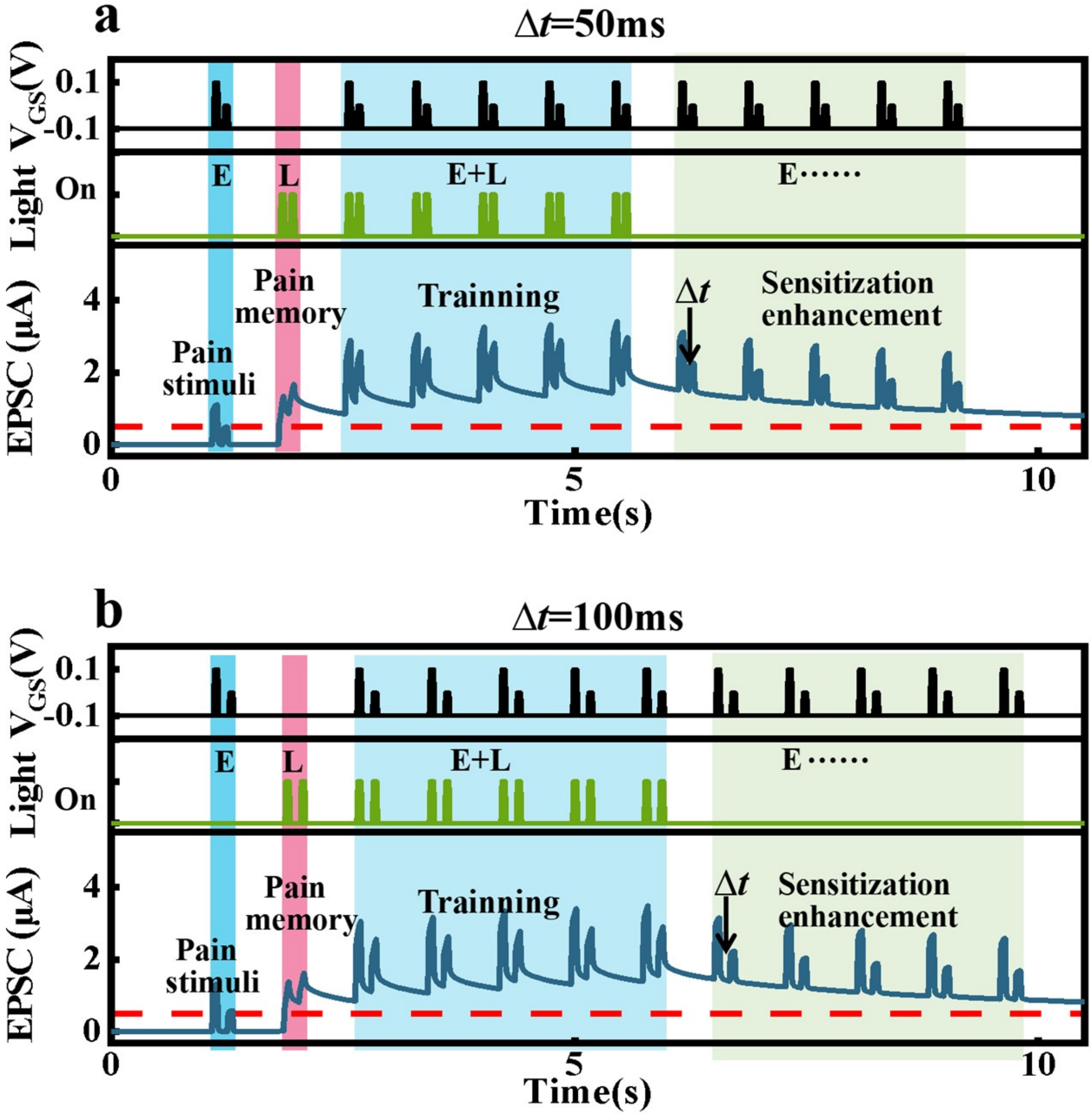
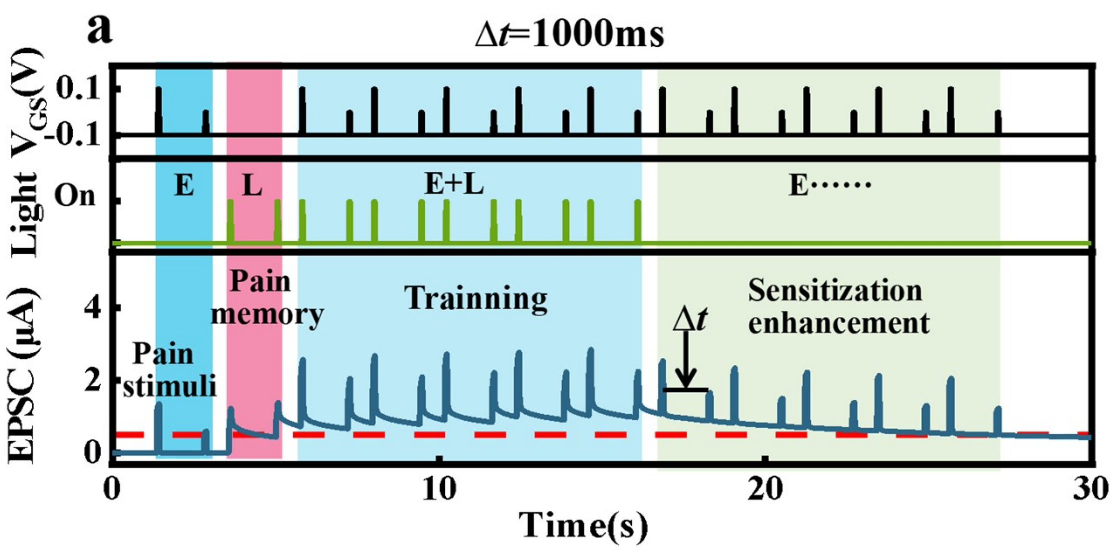



**Fig. S6** The sensitization degree with different time intervals between the two electrical spikes by the Pavlovian training process, and the body is in a mild central sensitization state initially. (a) $\Delta t$ = 50 ms. (b) $\Delta t$ = 100 ms.



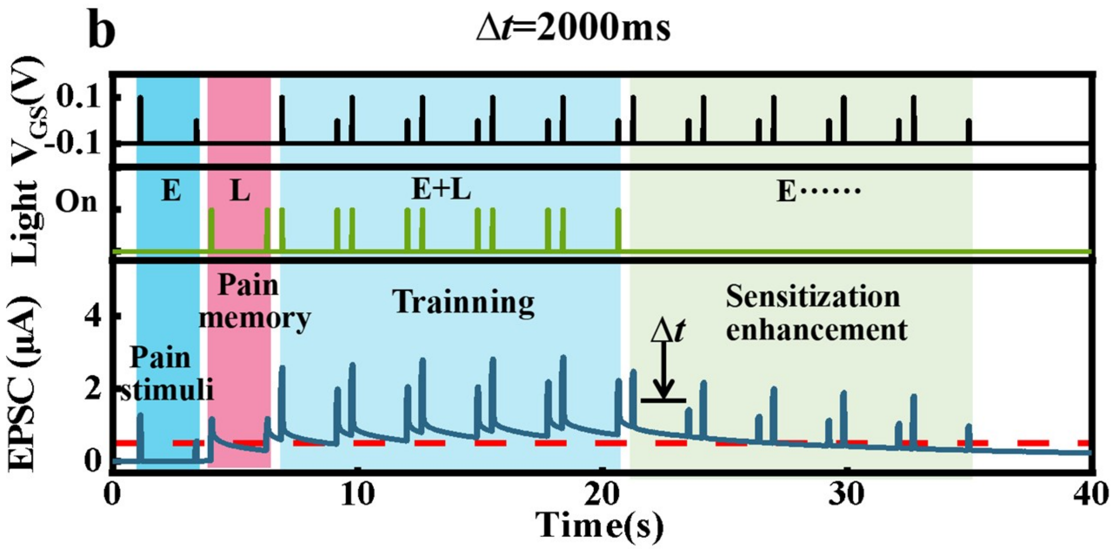




**Fig. S7** The sensitization degree with different time intervals between the two electrical spikes by the Pavlovian training process, and the body is in a mild central sensitization state initially. (a) $\Delta t$ = 1000 ms. (b) $\Delta t$ = 2000 ms.

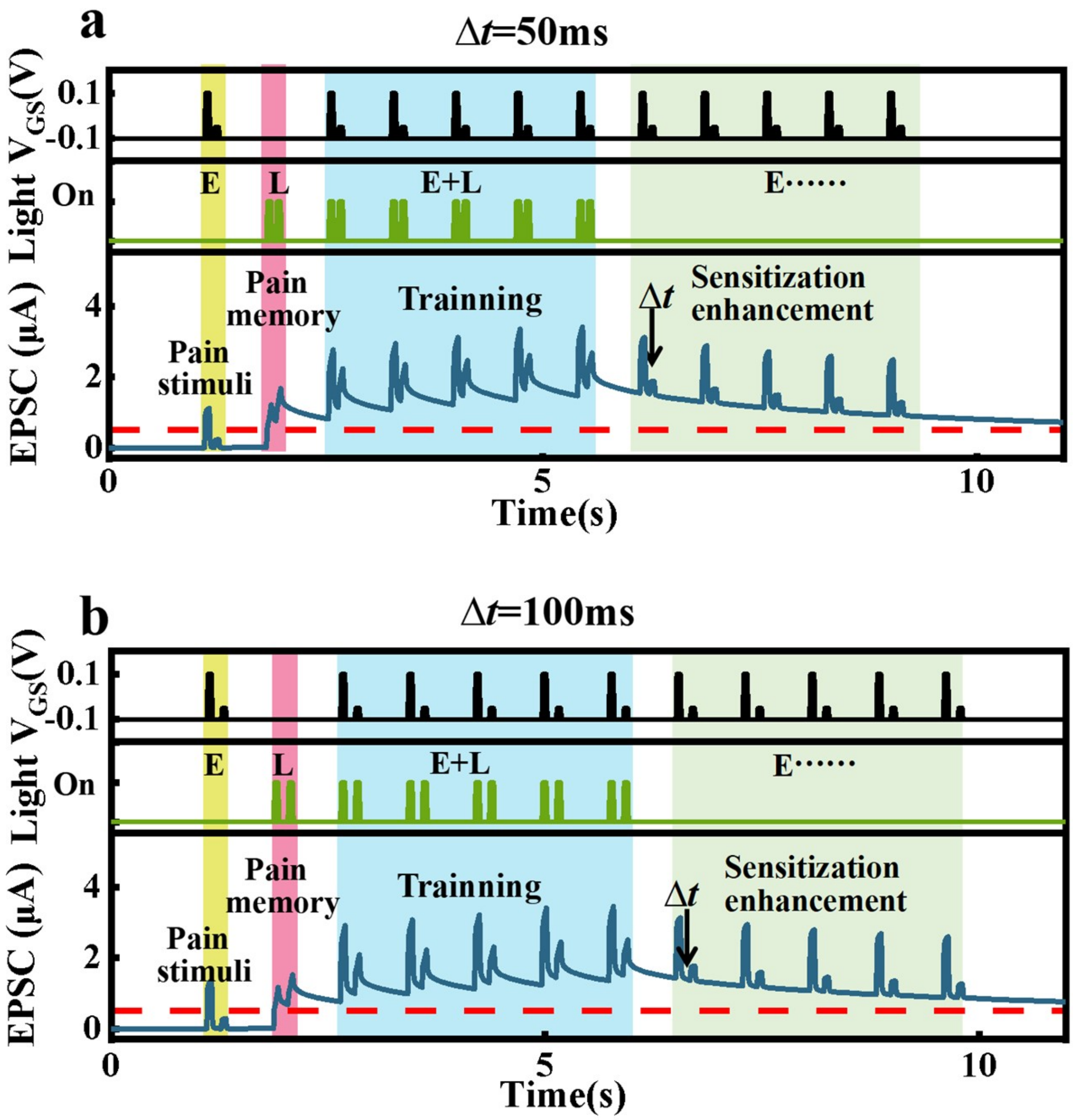



**Fig. S8** The sensitization degree with different time intervals between the two electrical spikes by the Pavlovian training process, and the body is in a normal injury state initially. (a) $\Delta t$ = 50 ms. (b) $\Delta t$ = 100 ms.

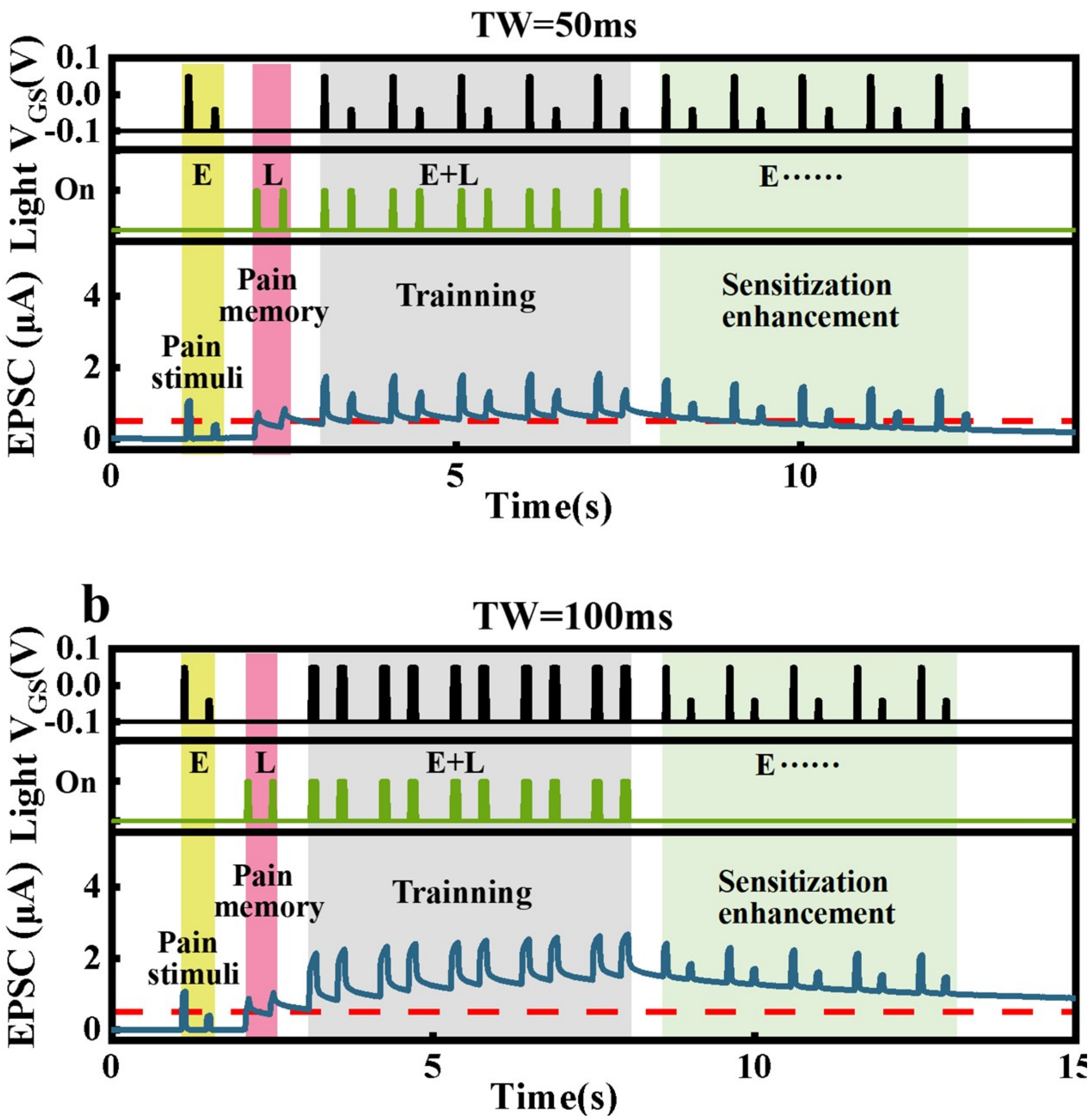



**Fig. S9** The cortical reorganization degree with different training pulse widths in the photoelectronic synergy training. (a) TW = 50 ms. (b) TW = 100 ms.

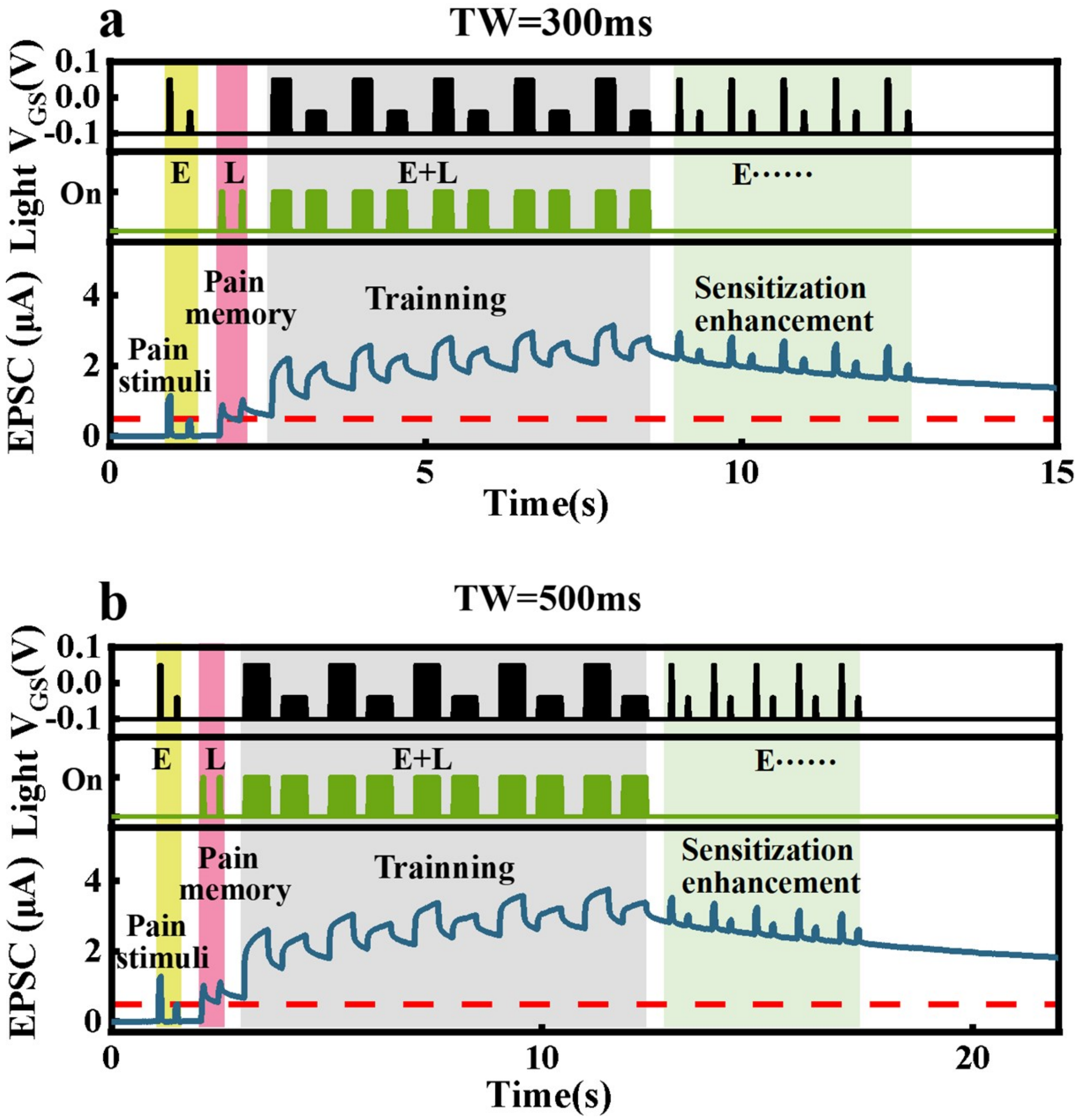



**Fig. S10** The cortical reorganization degree with different training pulse widths in the photoelectronic synergy training. (a) TW = 300 ms. (b) TW = 500 ms.

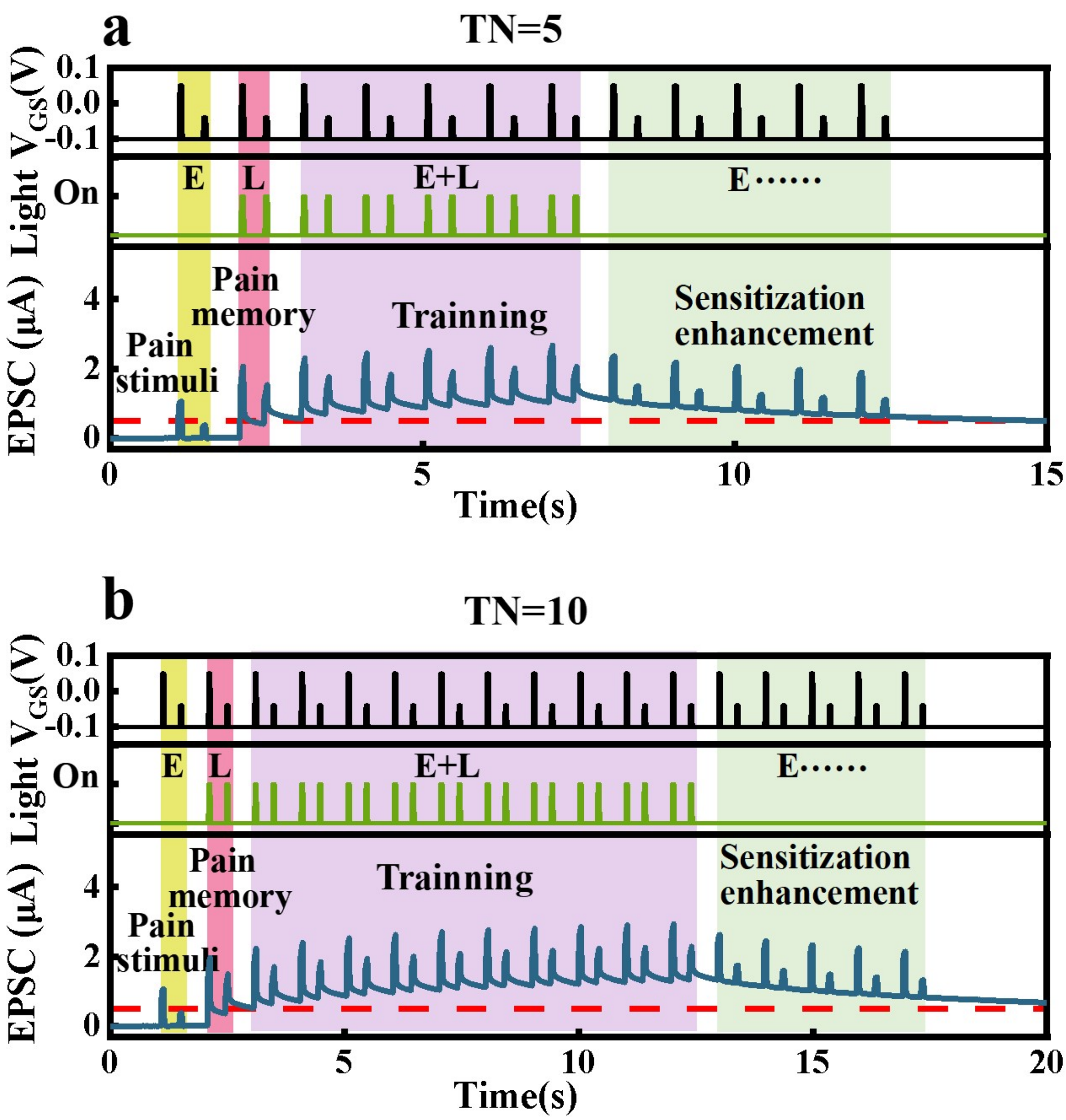



**Fig. S11** The cortical reorganization degree with different training numbers in the photoelectronic synergy training. (a) TN = 5. (b) TN = 10.

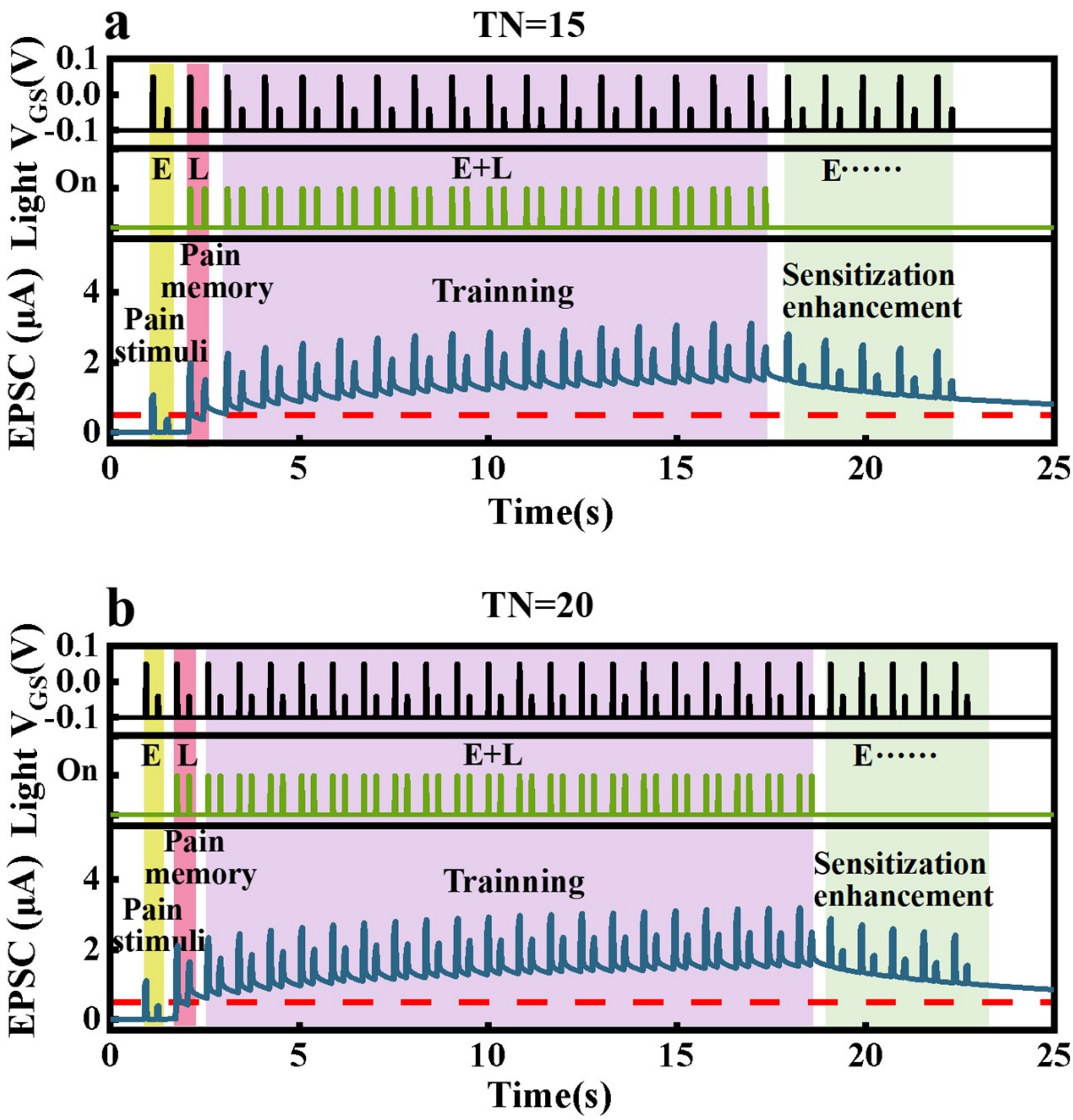



**Fig. S12** The cortical reorganization degree with different training numbers in the photoelectronic synergy training. (a) TN = 15. (b) TN = 20.

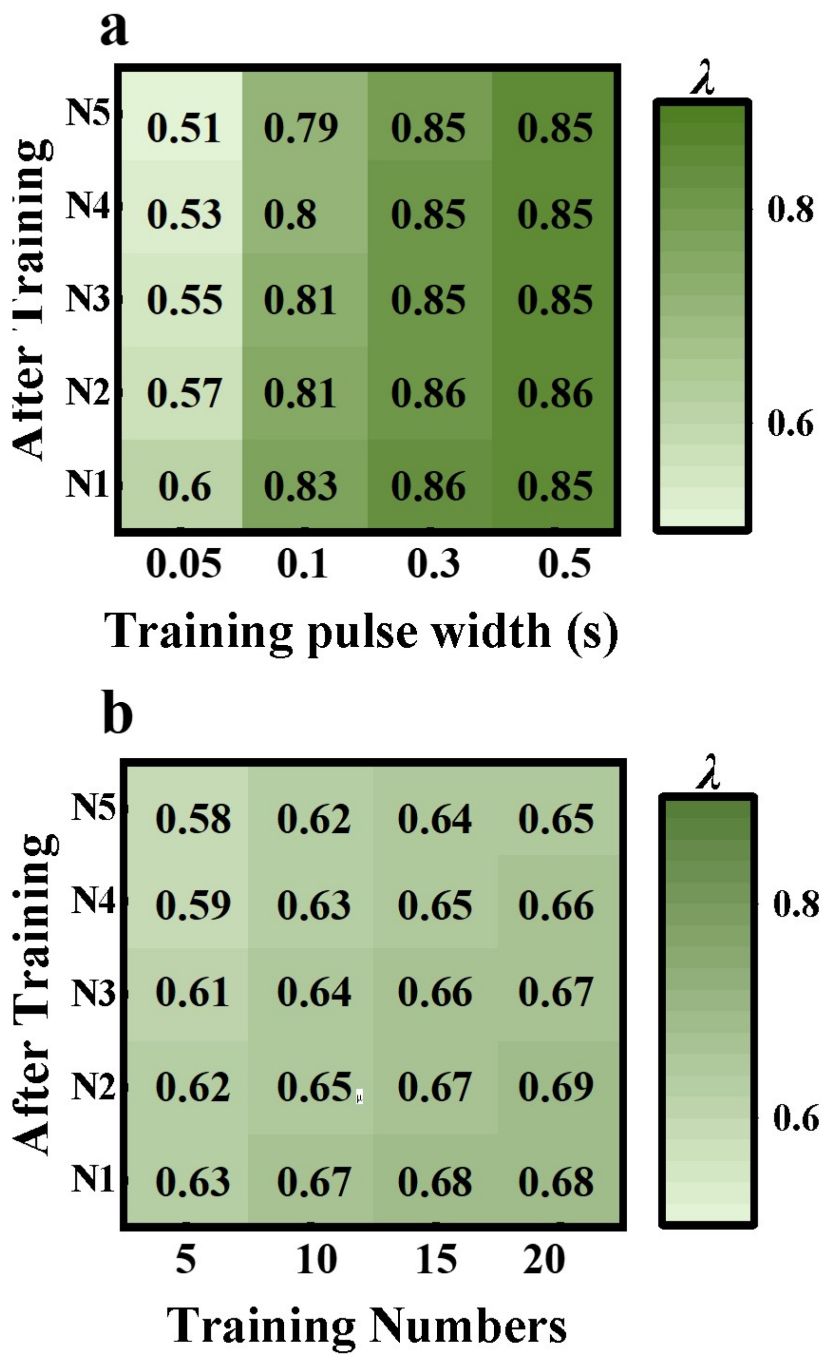



**Fig. S13** The detailed values of $\lambda$ are shown with (a) different spike durations in training and (b) different training numbers.

**Table S1.** The fitting results are summarized for Figure 4f in main text.

| External Stimulus | $\eta_0$ | $E_0$ |
|---|---|---|
| Electrical spike | 179.9 | -169.3 |
| 405nm laser | 237.9 | -186.7 |
| 360nm laser | 439.8 | -378.6 |

**Table S2.** The fitting results are summarized from Figure 4j in main text.

| External Stimulus | $\gamma_0$ | $F_0$ | $\tau$ |
|---|---|---|---|
| Electrical spike | 38.4 | 10.2 | 24.5 |
| 405nm laser | 109.8 | 32.8 | 5.7 |
| 360nm laser | 90.7 | 39.2 | 6.3 |