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Reconfigurable Memlogic Long Wave Infrared Sensing with Superconductors

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ABSTRACT

Superconductors possess advantages in two device categories: quantum-limited optical sensors covering a wide electromagnetic spectrum and quantum logic devices supporting computation beyond von Neumann architectures. Combining both categories presents an opportunity to revolutionize the sensory industry through in-sensor computing, reducing communication latency and power consumption. Additionally, optically encoded computation enables visual input for quantum computers and facilitates long-distance interactions between distributed systems. However, such attempts are still nascent, primarily focusing on new materials other than superconductors. Here, we report a superconducting niobium long-wave infrared sensor with logic and memory functions. Exploiting the bistability of superconducting nanowires, state transitions between normal and superconducting states can be triggered by combined optical and electrical pulses. The endurance performance, allowing for states persistence over time (>10⁵ s), exceeds conventional phase change memories. Utilizing these switchable characteristics, our memlogic sensor supports reconfigurable logic functions, making it suitable for encrypted communication applications. Enhanced by an in-situ resonant metamaterial absorber design, it achieves ultrahigh sensitivity in the long-wave infrared region (D* = 1.1 × 10¹⁵ Jone @ 12.2 μm m). This work establishes the foundation for all-in-one memlogic optical sensors based on the superconductor platform, surpassing human retina limitations and facilitating intelligent remote sensing, encrypted communication and visional-input superconducting quantum computer etc.

Since the discovery of superconductivity in 1911, it has garnered immense interest and found numerous indispensable applications¹. For instance, with regard to weak photo signal sensing², superconducting sensors can provide an unparalleled range of electromagnetic spectrum coverage-spanning from very low frequency microwaves to high frequency X-rays³,⁴ – in comparison to other
photodetection technologies. Meanwhile, ultimate sensitivity up to single photon level can be achieved in, e.g., near-infrared spectral range\(^6\), eventually enabling photon-based quantum computational advantage\(^6\). Additionally, superconducting qubits are the primary candidate for a scalable quantum processor\(^2\). Moreover, the bistability behavior and deterministic switching associated with superconducting phase transition causes memory effect and hence facilitates realization of memristor as building block for non-von Neumann architectures\(^8\) - \(^9\). By combining above optical sensing, quantum logic computing, and memory functionalities, a new chance to revolutionize the sensory industry is granted: The rapid development of artificial intelligence (AI) and the Internet of Things (IoT) has induced fast growth of sensory nodes generating an ever-increasing volume of unstructured and raw data that requires processing\(^10\). In this regard, the in-sensor computing provides a promising route to address the sensing/processing bottleneck by reducing power consumption, time delay and hardware redundancy\(^11\). Meanwhile, like the retina dominating the information input for biological systems, optically encoded logic devices bring a new degree of freedom to realize visual input capability for quantum computers and achieve long distance interactions between distributed systems in e.g., earth-based and/or deep space applications, where the spectral range is not limited to visible light but can be carefully selected, such as the atmospheric transmission windows.

Recent research on non-von Neumann superconducting neuromorphic circuits has made significant strides by utilizing quantum-phase slip junctions\(^12\) - \(^14\), Josephson junctions\(^15\) - \(^16\), magnetic Josephson junctions\(^17\), and superconducting nanowires\(^18\), which demonstrated memlogic operations with the speed improved to the order of ps/spike and energy dissipation to the order of aJ/spike. On the other hand, however, very few reported works\(^19\), \(^20\) have addressed the integration of optical perception with these memlogic devices, particularly in the long wave infrared atmospheric window. Notably, superconductors appear to be an ideal candidate to achieve in-sensor computing or memlogic sensing. Yet very few accomplished works exist. Previous reports related to memlogic sensors mainly relied on semiconductors\(^21\) and metal-oxides\(^21\), two dimensional materials like black phosphorus\(^22\), inherently limited in both sensitivity and detectable wavelength range.

Here, we present a superconducting sensor that combines the functions of ultrahigh sensitivity at LWIR, memory and reconfigurable logic computing. These functions stem from the high optical sensitivity and thermally bistable effect near the superconducting phase transition. To improve sensitivity at invisible wavelengths as exemplified here with \(\lambda\sim 12.2\ \mu m\) in the important atmospheric infrared window (8~14 \(\mu m\)), a resonant plasmonic cavity, with tri-layer structure of Nb-Si-Nb, is adopted in our sensor. With these advantages, our sensor can be programmed with both optical and electrical spikes, enabling electronic in-memory computing, in-sensor computing, optical remote programming and hence all-in-one single devices. The reconfigurable “AND”, “OR”, “signal follower” and more complex logic operations were demonstrated in our single memlogic sensor. With these reconfigurable operations, we show the optical remote encrypted communication at a single device level. As the bistable effect with the characteristics of high temperature sensitivity is ubiquitous in superconductors, our memlogic concept with superconducting phase transitions can be applied to a wide range of materials at a quantum limit level. Our work paves the way for reconfigurable digital logic, in-sensor computing, infrared remote sensing and encrypted communication with superconductors.

Results and discussion
Electrical controlling bistability. Figure 1a and 1b display the superconductor Nb wire circuit used in this study, which consisted of a grating wire with a width $W = 1.3 \, \mu m$, thickness of $h=60 \text{nm}$ and period of $P = 2.5 \, \mu m$. The device features a meander-shaped design, allowing for electrical measurements via four electrical contacts. Firstly, as shown in Fig.1c, we study the hysteretic current-voltage characteristic (IV) without intentional light illumination at different temperature between 6.5 and 7.5 K. The critical temperature of our device is about 7.3 K (see Supplementary Note 1, Fig. S1a). In a hysteretic IV curve, when the current is ramped up from zero, the device typically switches to a non-zero voltage state at the critical current $I_c$. The subsequent current ramp down gives a switching to zero-voltage state at a smaller current, called retrapping current $I_r$. In a conventional tunnel-barrier type Josephson junction, hysteresis arises from large junction capacitance. In a superconducting wire, it is now understood that hysteresis is of thermal origin. Now we focus on the equilibrium properties of our device’s critical current $I_c$ and retrapping current $I_r$. With an increase in temperature, the $I_c$, $I_r$ and hysteretic loop become smaller (Fig. 1c). Our finding suggest that the expression $I_c \approx I(0) \left[1 - \left(T/T_c\right)^2\right]$ from Silsbee’s rule^25 satisfactorily describes the behavior of our device, as depicted by the red line in Fig.1d. The fitting parameters $I(0) = 1.24 \, mA$, $T_c = 7.38 \, K$ represent the critical current at zero temperature and critical temperature respectively. According to Silsbee’s rule, if the magnetic field generated by the supercurrent at the surface of the sample becomes equal to the critical magnetic field, the superconductor changes into the dissipative intermediate state. When the device changes into the dissipative state, it will result in thermal runaway due to the Joule heating effect. Besides, the phase slip fluctuations can also trigger a thermal runaway giving a resistive hot spot (the voltage step in Fig 1c black line). In the case of poor heat evacuation, the device cannot return to the superconducting state until the heat generated by the Joule heating effect is smaller than the heat transferred to the substrate, corresponding to a threshold current. This threshold current is the retrapping current $I_r$ and, according to the hotspot mode^4, it can be expressed by $I_r = (\alpha W^2 T_c d/\rho)^{1/2} \left(1 - T/T_c\right)^{1/2}$, where $\alpha$, $W$, $d$, $\rho$, is heat-transfer coefficient per unit area, width, thickness and resistivity of the device, respectively. It can easily be calculated with classical thermal equilibrium theory which agrees well with our experimental data. In our case, $W = 1.3 \, \mu m$, $d = 60 \, \text{nm}$, $\rho = 1.56 \times 10^{-7} \, \Omega \cdot \text{m}$. Then we derived the fitting parameter $\alpha = 5.86 \, \text{W/cm}^2 \, \text{K}, T_c = 7.27 \, \text{K}$ from the fitting curve (black line) in Fig. 1c. The fitting parameter $\alpha$ agree well with previous literature^6.

When a bias current $I_{bias}$ is suddenly applied between the $I_r$ and $I_c$, $(I_r < I_{bias} < I_c)$, the device can be operated either in the superconducting zero voltage state (also known as low resistance state, LRS) or normal-non-zero voltage state (high resistance state, HRS), depending on the previous operations and state. This bistable effect can be controlled by electrical pulse. As shown in Fig. 1e, HRS is written using a high electrical pulse, erased using a low electrical pulse, and then this state is stored for more than $10^5$ seconds with no drift. Initially, the device operates at LRS with a current bias of $200 \, \mu A$ $(I_r < I_{bias} < I_c)$ at 6.5 K, then a high electrical pulse (400 $\mu A > I_c$, duration 0.3 s) switches the LRS to HRS. Because the high electrical pulse will generate a magnetic field larger than critical magnetic field, which would destroy the superconducting state. The device preserves HRS even when the current drops back to $200 \, \mu A > I_r$. At this time, heat generated by the Joule heating effect is higher than the heat transferred to the substrate, causing thermal runaway. Similarly, a low electrical pulse (30 $\mu A < I_r$, duration 0.3 s) switches the HRS to LRS and maintains LRS with the same current bias of $200 \, \mu A$ since the heat generated by Joule heating with low current is smaller than the cooling power, returning to the superconducting state (with almost zero resistance and no
Joule heating effect) when the bias current returns to the range of 200 μA ($I_r < I_{bias} < I_c$). The device has excellent repeatability and reliability, demonstrating no error bits during $10^6$ cycles of switching between HRS and LRS, as shown in Supplementary Note 1 Fig. S1b. The response time of writing and erasing is 2.2 μs and 1.9 μs, respectively. (see Supplementary Note 1, Fig. S1c). This is substantially faster than human response time which is on the order of millisecond. By utilizing superconductor as a memristor, the issues commonly found in other material-based memristors were successfully resolved. These concerns include instability observed in chalcogenide-based phase change materials (PCM) used in memristors, as well as the poor cycling endurance resulting from randomly-formed conduction channels and filament rupture observed in filamentary memristors.

Besides, the switching threshold between the Superconducting state and normal state is excellent for integrating and firing neuron applications. This threshold switching provides precise transitions between the subcritical and supercritical current states, making it very useful in simulating the functions of biological neurons.

**Optical controlling bistability.** So far, for most of the reported superconducting devices, such as superconducting quantum interference devices (SQUID) and superconducting photodetectors, this hysteretic IV was often considered as a hindrance to devices’ performance although they can be indeed utilized as switches or memories. By contrast, here we take the advantages of the hysteresis behavior and show its favorable applications in memlogic sensing.

In order to improve the LWIR absorption, a resonant plasmonic metamaterials absorber was adopted, which consists of two metallic elements: a 60 nm thick Nb grating resonator and 100 nm thick Nb ground plane, with a 280 nm thick Si dielectric layer spaced in between, as shown in insert Fig. 2a. The area of Nb grating resonator is $100 \times 100 \mu m^2$ with a typical length $L = 100 \mu m$, width $W = 1.3 \mu m$ and period $P = 2.5 \mu m$ and is connected in a meander-shape to allow electrical measurement. The Nb ground plane is thick enough to block the transmission of incident light. This three-layer metamaterial couples to both the magnetic and electric components of incident electromagnetic waves and allows for minimization of the reflectance, at a certain target frequency, by impedance matching to free space. As schematically shown in insert Fig. 2a, localized surface plasmons are excited along the short Nb wire axis when perpendicularly polarized light hits Nb wire. The plasmonic oscillation in upper Nb stripes causes an antiphase oscillating mirror counterpart in the Nb ground plane, resulting in a circular current and a magnetic response. The plasmonic resonant frequency of our sensor was measured to be $820 cm^{-1}$ (12.2 μm), as shown in insert Fig. 2d. The incident light was mainly absorbed by Nb wire due to the local plasmons (see Supplementary Note 2, Fig. S2). The local electric field was enhanced resonantly in the close vicinity of Nb wire with oscillating current inside. Thus, the Copper-pair will be destroyed efficiently when the light hits the Nb wire. Furthermore, the plasmonic resonant frequency can be easily tuned by changing the geometry of metamaterials, such as the width of the Nb wire (see Supplementary Note 3, Fig. S3). To simplify, it can be considered as a horizontal Fabry-Perot-like resonant mode, whose first-order resonance wavelength is roughly given by $\lambda_0 = 2n_{eff}W$, where $n_{eff}$ is the effective refraction index of the mode in the absorber cavity of width W. The absorption peak at resonant frequency reaches nearly 70% (Insert Fig.2d) and we can further enhance this peak absorption (see Supplementary Note 3, Fig. S3c) by optimizing the geometry of metamaterials to the perfect absorption condition. Consequently, this plasmonic structure enhances its efficiency in harvesting the target infrared light, which thereby triggers the superconducting phase transition with
extraordinarily high sensitivities.

As shown in Fig. 2a, the IV cures are significantly impacted by infrared light at its resonant frequency (820 cm^{-1}, 1.22 μm in wavelength) at varying intensities, due to the presence of a resonant plasmonic metamaterial absorber. Using optical pulses of varying intensity, we can manipulate the bistability of the device, as demonstrated in Fig. 2b. At a constant bias current of 125 μA, the device’s state was changed to HRS under the illumination of light 2 ((0.66 mW/cm^2, green line), reset to LRS upon illumination of light 0 (black line, indicating no illumination), and maintained its previous state upon illumination of light 1 (0.34 mW/cm^2, red line). The response time of writing and erasing by light is 5.4 ms and 4.5 ms, respectively, as shown in Supplementary Fig. S4. This illustrates the optical memlogic function of the device. Under illumination of light 1, the device’s state can be either HRS or LRS, depending on the pre-existing memory state.

The physics underlying the optical controlling of bistability can be explained by examining \( I_r \) and \( I_c \). The effect of incident photons is to reduce the free-energy barrier of phase slips in the superconductor, thereby causing a proliferation of phase-slip events and leading to a superconducting transition^{15}. This reduces \( I_c \), which is given by \( I_c(P) = I_0 - AP \), where \( P \) is the light power, \( I_0 \) is the critical current without light radiation, and \( A \) is an adjustable parameter^{24}. In our experiment, we found that \( I_0 = 0.215 \, mA \) and \( A = 0.245 \, A \cdot cm^2/W \). On the other hand, the \( I_r \) is determined by classical thermal balance. In addition to Joule heat, the incident light will induce an additional heating source. Hence, we assumed that \( I_r(P) = (aW^2T_Cd/\rho)^{1/2}(1 - T/T_C - \beta d/(aT_C \cdot P))^{1/2} \), where \( \beta \) is an adjustable parameter. The derivation of this formula can be found in Supplementary Note 5. The fitting parameter \( \beta = 6.35 \times 10^{15} \, K^2/m \), \( \alpha = 5.82 \, W/cm^2 \, K \), \( T_C = 7.07 \, K \). Our model for \( I_c(P) \) and \( I_r(P) \) fits well with our experimental data, as shown in Fig. 2c. Our resonant plasmonic metamaterials absorber can harvest light efficiently, enhancing the parameter \( A \) and \( \beta \), thus suppressing the \( I_c \) and \( I_r \). This explains the device’s optical switching bistability. Specifically, at a bias current of 125 μA and 6.5 K, light 2 destroys large quantities of Cooper pairs and reduce the free-energy barrier of phase slips, resulting in proliferation in the phase-slip events and causing the device to switch to HRS when \( I_{bias} > I_c(P) \). The light 0 switches the HRS to LRS due to smaller heat generated by Joule heating and optical power, resulting in \( I_{bias} < I_c(P) \). Light 1 causes the \( I_{bias} \) to fall between \( I_r(P) \) and \( I_c(P) \), leading to bistability and memlogic function.

The responsivity of the device can be calculated using the expression \( R_{vc} = (V_P - V_0)/P \), where the \( V_P \) and \( V_0 \) represent the voltage of device under irradiation of infrared light with power \( P \), and without intentional light illumination, respectively. When the device is operated in the superconducting state with \( I_{bias} < I_c(P) \), the voltage can be considered almost zero. Therefore, \( R_{vc} = (I_0 - AP)R/P \), where \( R \) is the resistance of normal state. The responsivity is related to the temperature and illumination power, with smaller temperatures leading to larger responsivities. As shown in Fig. 2d (detail seen in method), our device demonstrates an ultrahigh responsivity of 1.9 \times 10^6 \, V/W at the plasmonic resonant frequency with illumination power of 9.2 nW at 6.5 K. Noting the thermal noise of resistance to be dominant in low photon-flux condition, the minimum noise equivalent power of our device is 8.9 \times 10^{-18} \, W, and the detectivity is \( D^* = 1.1 \times 10^{15} \) Jones, which is the best sensitive performance of superconducting nanowire detector at 12.2 μm to our knowledge. The responsivity of the device can be further increased by operating it at lower temperatures and lower illumination power. From the simple equation for \( R_{vc} \), it can be deduced that lower temperature leads to larger responsivity, just like our experimental data (Fig. 2d).
Additionally, there exists a minimum power that can trigger phase slip events and lead to superconducting transition. Our plasmonic structure enhances the device's efficiency in harvesting the target infrared light, thereby lowering power. In our case (See Supplementary Note 6), the measured minimum power that can trigger the phaseslip events is 23 μW/cm² (2.3 nW in sensor) at 6.5K, corresponding to biggest responsivity 7.4 × 10⁸ V/W.

This unique optical controlling bistability characteristic can be applied in optical information encryption transmission. Figure 3 shows a schematic diagram and measured data for this application. A binary picture "F" was first converted to a one-dimensional array ASCII and then encrypted using an algorithm based on the device's truth table. The laser then transmits the encrypted information to the sensor. If an enemy intercept the information on this process with the traditional sensor (such as power meter), he will obtain one-dimensional array with three different types of intensity. The measured data was showed in right bottom of Figure 3. On the traditional way, one may set a threshold value, when the value bigger than threshold value can be regarded as 1, otherwise 0. This is completely wrong for decrypting our information because the middling intensity (light 1) cannot be simply regarded as 0 or 1; it depends on the previous state. On the contrary, our memlogic sensors automatic decrypted the information thanks to its memlogic functions (right top of Figure 3).

Reconfigurable memlogic circuit. In addition to the pure electrical/optical switching characteristic, we next programmed the device using cooperatively optical stimulations and electrical pulse. Ten repeated cycle hysteretic IV curves with illumination of 0.5 mW/cm² (red curves) and without intentional light illumination (black curves) were shown in Fig. 4a, respectively, demonstrating its excellent repeatability and robustness. We defined operating bias current zone as A, B, C, D and E for \( I_{bias} < 93 \mu A \), \( 93 \mu A < I_{bias} < 124.2 \mu A \), \( 124.2 \mu A < I_{bias} < 157.2 \mu A \), \( 157.2 \mu A < I_{bias} < 223.2 \mu A \) and \( 223.2 \mu A < I_{bias} \), respectively. In one instance, the device initially operated at LRS with a bias current of 180 μA (D zone), it was switched to HRS under the light illumination from a Quantum Cascade Laser (QCL) with a wavelength of 12.2 μm, a power density of 0.5 mW/cm², and a duration of 0.3 s. The device retained the HRS even after the light was removed. The reset process was initiated by an electrical pulse (1 μA, 0.3 s), shown in Fig. 4b. In another case, the device initially operated at LRS with a bias current of 110 μA (B zone) and illumination with a power density of 0.5 mW/cm². The set process was induced by a high electrical pulse (400 μA, 0.3 s), The reset occurred after sudden cessation of the light (0.3 s), as illustrated in Figure 4c. These cooperative optical stimulation and electrical pulse-based set/reset processes were highly repeatable and robust (Figures 4b and 4c).

When the devices were operated at different zone of constant bias current, it performed different functions. This non-volatile optoelectronic switching characteristics of our sensor can be further applied in reconfigurable sequential memlogic circuits, as shown schematically in Fig. 4b. This memlogic circuit consists of two inputs (light signal and memory state), one electrical selector and one output. When operated at current bias in B, C and D zones, this memlogic device performs the “AND”, “light signal follower” and “OR” functions, respectively. For instance, during “AND” operation, only the combination of light on (1) and memory state HRS (1) results in an HRS output. The initial HRS can be obtained by a high electrical pulse (400 μA, 0.1 s). When we operate the sensor at a bias current in zone B, the output follows the light on/off. At the bias current in zone D, the output is LRS (0) only when the light is off (0) and LRS memory state. The testing data is shown in Fig. 4e. A more complex logic function can be generated by applying a square wave current
between the B, C, and D zones. In this way, the output depends not only on the light signal input and memory state but also on the biased current state. The truth table and testing data for sequential logic were shown in Fig. 4f and Fig. 4g, respectively. The bias current was established 100 ms before the optical input signal during the test. Achieving these sequential logic functions in a single device eliminates the need for integration of several devices that is usually required with conventional CMOS devices. Therefore, the optical and electrical-set/reset operations allow the present single device to be a reconfigurable logic element that may be used to switch between different algorithms to efficiently reduce the circuit complexity and increase the effective integrating density of the processor chip. All the above sequential logic functions being achieved in a single device level may provide promising applications in a reconfigurable superconducting logic circuit, superconducting computer and intelligent remote sensing and communications, as we exemplify in the following.

Figure 5. demonstrates the implementation of optically encrypted information transmission using our sensor’s reconfigurable memlogic capabilities. We obtained diverse information from the same optical signal by operating the sensor at different bias currents corresponding to distinct keys, as shown Figs. 5b, 5c and 5d. The square wave bias current between B and C, the constant bias current C and the square wave bias current between C and D represent the blue, red and green keys, respectively. Only the correct key will allow the user to access the correct information. The encrypted method demonstrated in Figure 3 ensures security during transmission. Correct information can only be accessed using the appropriate key, providing an additional layer of security in terminal equipment, as illustrated in Figure 5. Compared to other visible light encrypted technology\textsuperscript{35,36}, the invisible infrared light implemented here in encrypted information transmission brings more spectral freedom and may be more beneficial for confidentiality because the correct information is prevented from being intercepted by other (conventional) infrared sensors or similar sensors without the correct key.

We conducted further investigations into the transmission of multiple states of light intensity. In Fig. 6a, various IV curves are displayed under light illumination with four different power densities (0 for light off, and 1-3 corresponding to 0.19, 0.37, and 0.65 mW/cm\textsuperscript{2}). Under illumination by each light intensity state, the device operating at the bias current in A\textsubscript{5}, B\textsubscript{5}, C\textsubscript{5}, D\textsubscript{5} and E\textsubscript{5} zones will yield five different truth tables, respectively, as illustrated in Fig. 6b. Figure 6c presents the sequential logic testing data. These four light intensity states are compressed into the HRS and LRS on the devices and can be distinguished by operating at different bias currents. When operating at the bias current in C\textsubscript{5}, it functions as an analog to digital converter (ADC) converting an analog light signal (>0.37 mW/cm\textsuperscript{2}) to digital 1 (HRS) and a light signal (<0.19 mW/cm\textsuperscript{2}) to digital 0 (LRS). What’s more, it can generate more information due to memlogic characteristics. Theoretically, if there are N kinds of light intensity states, and the regions included in the corresponding IV hysteresis curve do not overlap, then 2N-3 different truth tables will be generated under operation at certain bias current. Fig. 6b and Supplementary Fig. S6 showed 4 and 3 light intensity states that corresponded to 5 and 3 different truth tables, respectively. Figure 6d displays the image encoded by 4 kinds of light intensity. This image is arranged in a one-dimensional array from various directions and then sent to the sensor. The sensor yields five different images when operated at five different current bias (A\textsubscript{5}, B\textsubscript{5}, C\textsubscript{5}, D\textsubscript{5} and E\textsubscript{5}). Additionally, the memlogic feature of the device in regions B\textsubscript{2} and D\textsubscript{2} results in a unique image under the illumination of different light sequences in various directions (Up, Down, Right, Left), as shown in Fig. 6e. This method of multi-value optical information compression and restoration also provides a new way for the encrypted
transmission of information. Moreover, suppose the device is made into an array and works in
different bias current regions. In that case, the parallel transmission of optical information can be
realized, as shown in Supplementary Fig. S7.

In conclusion, our study showcases a memlogic Nb sensor integrating the function of ultrahigh
sensitivity long wave infrared detection, memory and reconfigurable logic computing. Based on in-
sensor computing architectures, we introduced an optical encryption transmission technique. These
functions demonstrated in our work can also be achieved with high temperature superconductor,
since the bistable effect is common for superconductors. Our work opens a new avenue for
superconducting energy-efficient in-sensor computing and intelligent infrared sensing and
communication.

Methods

Sample and device fabrication. The memlogic device contained three layers 60 nm/280 nm/100
nm Nb/Si/Nb. The bottom metal mirror was patterned using UV lithography and 100 nm Nb was
deposited on thermally oxidized Si wafers using a magnetron sputtering machine. The base pressure
during deposition was less than \(3 \times 10^{-7}\) torr, with a deposition rate of \(\sim 3.7\) Å, DC power of 200
W, and Ar gas pressure of 2 mtorr. The bottom layer’s area is \(400 \mu m \times 400 \mu m\), which is smaller
than that of wafers and larger than that of the top layer. A 280 nm continuous Si film was then
deposited on the bottom layer and thermally oxidized Si wafers by the same magnetron sputtering
machine with a base pressure of less than \(3 \times 10^{-7}\) torr (at a rate of \(\sim 0.8\) Å with an RF power of
150 W and Ar gas pressure of 2 mtorr). The top layer of 60 nm thick Nb continuous film was deposited
on Si film and a 2 nm Si film was then deposited on Nb film to prevent oxidation. The top layer was
patterned using e-beam lithography (EBL) with negative electron beam photoresist AR7520, and the
exposed area was then etched by Reactive Ion Etching (RIE) with CF4 gas.

Optical spectrum measurements. The optical reflectance spectrum (R) of the device was measured
by FTIR system (Burke V80, 15X objective) at room temperature with the normalized background
of the reflectance spectrum of the gold reflector. The absorption spectrum (A) was determined as
\(A=1-R\) considering that the bottom layer of the 100 nm Nb reflector blocks light transmission (\(T=0\)).
In addition, a polarizer was used to obtain the polarized light, with the electrical filed being almost
perpendicular to short axis of Nb wire.

Optical and Electrical measurements. All electrical measurements were carried out in variable
temperature cryostat with ±3 mK stability (PHYSIKE: Qcryo S cryo S-300). I-V hysteresis,
endurance and retention test were measured by home-built LabVIEW programs with constant
current source (Keithley 2450) and voltmeter (Keithley DM6500). The duration of each bias current
point is 100 ms, when measuring the I-V hysteresis curve. The time response of electric pulse
switching between the HRS and LRS was measured by connecting a series 10 KΩ resistance to a
square wave voltage that ranged from 0.1 V and 5 V. An oscilloscope (Tektronix: MDO3014) recorded
this time response, as shown in Fig S3c. The square wave was generated by an arbitrary function
generator. (Tektronix: AFG 31000)

The optical characteristic of the memlogic device was measured by a tunable quantum cascade
laser (MOLECULAR VISTA: LASB0000-C-0006) with a repetition of 0.5 MHz and duration of 100
ns. Two polarizers were placed in QCL box. The power density of light was tunable by adjusting the angle of one of the polarizers and was detected by a power meter (Thorlabs: S401C). The responsivity (R) is defined as \( R = \frac{\text{Voltage}_{\text{light on}} - \text{Voltage}_{\text{dark}}}{\text{Power}} \). As shown in Fig. 2d, we measure the responsivity by sweeping current bias at each fixed temperature point with light on and light off. At a certain temperature, the max responsivity is derived from the voltage of the normal state induced by light minus the voltage of superconducting state at dark (almost zero). From this point of view, the noise of normal state resistance mainly affects the performance of the sensor. Then, we can calculate the NEP of the device by \( \text{NEP} = \frac{\sqrt{4k_B T R}}{R_V} \), where, \( k_B, T, R, R_V \) is Boltzmann constant, temperature, resistance, and responsivity, respectively. The normalized detectivity (\( D^* \)) of the sensor is a unified metric for evaluating all different photodetectors and is defined as the reciprocal of the NEP normalized by both the sensing area (A) and electrical bandwidth (\( \Delta f \)) and expressed by the following equation \( D^* = \frac{\sqrt{A f}}{\text{NEP}} \). The time response of light switching the HRS and LRS of device was recorded by oscilloscope at 6.5 K with constant current bias provided by SourceMeter (Keithley 2450), as shown in Fig S6.

**Memlogic characteristic and application.** The memlogic characteristic and applications were measured by home-built Labview programs. During the sequential logic test, as shown in Fig. 4g and Figs. 5 b-d, we programmed the polarizing rotary motor and source meter to generate Optical and electrical synchronizing signals.

**Data availability**
The data that support the findings of this study are available from the corresponding authors upon reasonable request.

**References**


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Author contributions
B.X.C, Z.H.A and Y.R.S conceived the project. B.X.C designed and fabricated the sensor, built the experimental setup, carried out the measurements and analyze data. L.P.Z contributed to sensor fabrication. B.X.C, H.P, H.Y.X, Y.R.S and Z.H.A prepared the manuscript and discussed the results.

Competing interests
The authors declare no competing interests.

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Fig. 1 | Characterization of electrical controlling bistability. a, Schematic depiction of a device. b, Optical micrograph of pseudo-color memlogic sensor. Four-probe method was used with constant current source meter during the measurement. Scale bar 50 μm. Inset: SEM image of part of photosensitive area. Scale bar 5 μm. c, Different I-V hysteretic curves under various temperature. d, Critical current and retrapping current change with temperature. e, Retention and electrical switching of HRS and LRS at 6.5 K. A high pulse current (400 μA, duration 0.3 s) was used for the set process, and the reset process was initiated by low pulse current (1 μA, duration 0.3 s), reading with current of 200 μA.
**Fig. 2** Optical controlling bistability. **a**, Different I-V hysteretic curves under the illumination of infrared light (820 cm⁻²) with different intensity at 6.5 K. The green, red and black curves represent the light intensity of 0.66 mW/cm², 0.34 mW/cm² and 0, respectively. Insert: Schematic depiction of a plasmonic absorber. **b**, Resistance switching through light pulse (duration of 0.3 s), read at current of 125 μA. **c**, The experimental data and fitting model for retrapping current and critical current, which decrease as the light power increases. **d**, The temperature and current dependence of responsivity. The lower temperature, the higher responsivity. Insert: Absorption spectrum of the sensor shows the metamaterials resonance frequency at 820 cm⁻¹ (wavelength 12.2 μm).

**Fig. 3** Optical bistability applied in encryption. A binary picture “F” was firstly changed to one-dimensional array ASCII, and then was encrypted by algorithm basing on devices’ truth table. Next the laser will transmit the encrypted information with three types of intensity of light power to the sensor. The enemy intercept the information with the traditional sensor (such as power meter) and obtains a false picture with three different types of intensity because
the light 1 cannot be simply regarded as logic 0 or 1. Only the friend obtains the right picture with our memlogic infrared sensor, which automatically decrypted the information thanks to its memlogic functions.

**Fig. 4** | Reconfigurable memlogic characteristics. **a**, Ten cycles sweeping I-V hysteretic curves of memlogic sensor with (solid red line) and without (solid black line) light illumination (0.5 mW/cm²) at 6.3 K. **b**, Write to HRS by optical pulse (0.5 mW/cm², duration of 0.3 s), and ease to LRS by low electrical pulse (1 μA, duration of 0.3 s), reading at 180 μA with light off. **c**, High electrical pulse (400 μA, duration of 0.3 s) was used to switch the LRS to HRS with light illumination (0.5 mW/cm²). The HRS is switched to LRS by turning off light with duration of 0.3 s. Reading operated at current of 110 μA. **d**, schematic of reconfigurable memlogic device and circuit design. The device can used as AND, light signal follower and OR, respectively. **e**, Output of AND, follower and OR operation. **f**, Truth table for square wave bias current operation. **g**, Testing data of square wave bias current operation.
Fig. 5 | Information encryption for implementation of reconfigurable memlogic sensor. a, Schematic diagram of decoding information with different key. b, c and d showing the information obtained by User1, User 2 and User 3 with blue key (square wave current bias between B and C zone), red key (constant current bias at C), and green key (square wave current bias between C and D zone, respectively. The B, C, and D were indicated at Fig. 4a.
Fig. 6 | Controlled by multiple state of light and bias current. a, I-V curve for device under light illumination with intensity of 0, 1 (0.19 mW/cm²), 2 (0.38 mW/cm²) and 3 (0.65 mW/cm²) at 6.5 K. The zone of A₂, B₂, C₂, D₂ and E₂ represent bias current 68 μA < Ibas < 75 μA, 75 μA < Ibas < 96 μA, 96 μA < Ibas < 103 μA, 103 μA < Ibas < 135 μA and 135 μA < Ibias < 144 μA, respectively. b, Truth table for device under the operation of A₂, B₂, C₂, D₂ and E₂, respectively. c, Output of resistance under the operation of A₂, B₂, C₂, D₂ and E₂. d, The input light image with four states of light intensity. e, The different output image of device under the different reading current and different direction of light signal transmission.
Supplementary Files

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