OPTOELECTRONICS LETTERS Vol.20 No.5, 15 May 2024

Lateral photovoltaic effect in the Ni-SiO_2-Si structure with bias

LING Xiang[1], ZHU Pengfei[1,2]*, ZHU Kun[2], SONG Pei[1], and LI Xiong[3]

1. School of Mathematics, Physics and Statistics, Shanghai University of Engineering Science, Shanghai 201600, China

2. School of Electrical Engineering, Liupanshui Normal University, Liupanshui 553004, China

3. School of Railway Telecommunication, Hunan Technical College of Railway High-speed, Hengyang 421002, China

(Received 8 June 2023; Revised 2 December 2023)

We designed a clamping device to study lateral photovoltaic effect (LPE) in Ni-SiO_2-Si structure with bias due to the appropriate barrier height. The LPE has a prominent sensitivity and linearity with 532 nm wavelength laser. The transient response time is 450 μs and the relaxation time is 2 250 μs in the Ni-SiO_2-Si structure without bias. The LPE sensitivity has a significant improvement with bias. The transient response time is 6 μs and the relaxion time is 47 μs with −7 V bias, not only improving the LPE sensitivity, but also increasing the response speed with bias. The research shows that the Schottky barrier structure can improve the sensitivity and linearity of LPE with bias effectively, and thus it can be used in position sensitive sensors.

Document code: A **Article ID:** 1673-1905(2024)05-0257-8

DOI https://doi.org/10.1007/s11801-024-3101-x

Since the lateral photovoltaic effect (LPE) was first discovered by SCHOTTKY W in 1930 and then developed by WALLMARK J T in 1957[1-3], researchers mainly conducted research on pn junction[4-8], metal-semiconductor (MS)[9] and metal-oxide-semiconductor (MOS) structures. The MOS structure had attracted in-depth research with advantages of easy fabrication and low cost by WANG et al[10-13]. The MOS structure is mainly composed of a layer nanoscale metal film covering semiconductors with a native oxide layer. Excellent LPE sensitivity was achieved in MOS structures, where Ti, Co, Ni, etc were fabricated to metal films[9,10,14]. High electrical resistivity and a large work function of the metal film in MOS structure would obtain the larger LPE[15]. Currently, almost suitable metals had been studied in MOS structures, and researchers had paid their attention to regulate LPE, where regulating ways include magnetic field[16], low temperature[17], bias[18], etc. The principle of LPE regulation is based on the change of Schottky barrier height. According to the LPE theory based on the continuity equation of current proposed by NIU et al[19], LPE is positively correlated with the number of carriers entering the semiconductor body from the pn junction per unit time and unit region, and the height of the Schottky barrier determines the number of carriers entering the semiconductor layer. Ni metal has characteristics such as high melting point, corrosion resistance, oxidation resistance, good ductility, easy alloying, and the appropriate Schottky barrier height was formed when Ni contracted to Si semiconductor. In order to study regulating LPE, we conducted our research in Ni-SiO_2-Si structure with bias. LPE is widely used in photoelectric detectors, position sensitive sensors, medical measurement and micro displacement precision measuring instruments due to the prominent linearity and sensitivity of LPE[9]. At present, most of research is focused on novel material films to enhance LPE[20-22], lacking the improvement of research methods. The valuation indicators of LPE include sensitivity and response speed. However, the previous regulation of LPE only involved sensitivity in MOS structure[23], we studied the LPE response speed with bias, and the application method of bias had been changed. This paper provides a research method for regulating the sensitivity and response speed of LPE, which changes the height of the Schottky barrier in Ni-SiO_2-Si structure with bias. The Ni-SiO_2-Si structure is a potential application in sensor with bias.

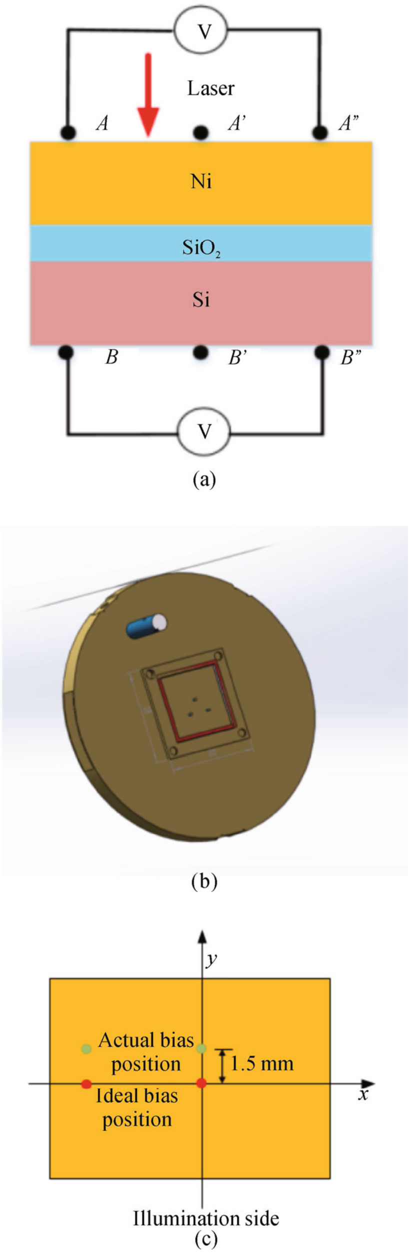
The experiments were carried out in the Ni-SiO_2-Si structure, an n-type silicon (Si) (1 1 1) substrate with 50—80 Ω·cm was prepared, and the silicon wafer was cut into rectangle of 20 mm×20 mm. The reliability change analysis (RCA) cleaning method was used to clean Si substrates[24]. The Si substrates were immersed in the de-ionized (DI) H_2O: NH_4OH: H_2O_2 (5: 1: 1) at 80 °C for 10 min (called SC-1). Followed step (called SC-2) metallic contaminants were removed by using DI H_2O: HCL: H_2O_2 (6: 1: 1) at 80 °C for 10 min. And SC-1 and SC-2 would be used repeatedly. The Si wafers then

---

* E-mail: zpf@sues.edu.cn

were rinsed under DI water for 30 min and subsequently blow dry using N_2 gas at 100 °C for 2 h. The 4-nm-thick Ni thin films were prepared by DC magnetron sputtering to be coated on the Si substrate with 1.2-nm-thick native SiO_2 layer, forming a stable Ni-SiO_2-Si structure. The film thickness and the deposition rate are measured by step profiler. The schematic diagram of lateral photovoltage (LPV) measurement is shown in Fig.1(a). The laser spot size was controlled at 60 μm, A, A', A'', B, B', B'' are electrodes points, and AA''=BB''=2 mm. We had designed a Ni-SiO_2-Si structure clamping device which can change bias application method as shown in Fig.1(b). Three spring needles are embedded in the clamping device, the backlight of Ni-SiO_2-Si structure is pressed by an acrylic plate to contract three spring needles, a spring needle is diagonally inserted to contract to the illumination side of Ni-SiO_2-Si structure with bias, the material of the spring needles is copper plated gold, and the diameter of spring needle is 0.38 mm. We connect the copper wire at the end of the spring needle to the voltmeter or oscilloscope to measure LPE and LPE transient response. However, the light is blocked in the illumination side when clamping the spring needle, the LPE was measured on the back of the Ni-SiO_2-Si structure (Si side) in this paper, and the LPE on the back side is smaller than that on the illumination side (Ni side) generally[9]. And in order to avoid interference from the clamping device when the laser scans along the two electrodes, the electrodes on the illumination side will be set 2 mm above the corresponding electrode points on the backlight side as shown in Fig.1(c). The laser power was controlled by polarizer and small hole which was detected by a power meter. The voltage source was used and *I-V* curve was measured by Keithley 2401 source meters. A 532 nm pulse laser with width of 50 ms and 500 MHz digital oscilloscope are used to measure the LPE response process. We used a UV-2600 spectrophotometer to measure the absorbance of Ni-SiO_2-Si structures. Sensitivity and linearity were fitted, where LPV has a dependence on laser position by the Origin software.

The atomic force microscope (AFM) topography of Ni-SiO_2-Si structure is shown in Fig.2(a), where root mean square (RMS) of surface is 208.6 pm. The transverse *I-V* curve of Ni-SiO_2-Si structure shows good ohmic contact between electrodes and the metal film, as shown in Fig.2(b), and the transverse *I-V* curves of several other electrode points also exhibit linearity. The vertical *I-V* curve shows that Schottky barrier is formed in the Ni-SiO_2-Si structure, and the Schottky barrier distribution is uniform relatively, as shown in Fig.2(c). The schematic diagram of barrier structure of the Ni-SiO_2-Si structure is shown in Fig.2(d). According to the vertical *I-V* characteristic curve, the electrons flow from the high Fermi level to the low Fermi level when Ni contacts the n-type Si semiconductor, and the electrons on the semiconductor surface flow into the metal layer, the energy band bends upward to form a Schottky barrier which builds a built-in electric field, and the direction is from the semiconductor to the metal.



(a)

(b)

(c)

Fig.1 (a) Schematic diagram of LPE in Ni-SiO_2-Si structure; (b) Isometric drawing of clamping parts; (c) Schematic diagram of the bias application position in Ni-SiO_2-Si structure

When the laser with enough energy is greater than the band gap of the semiconductor irradiated on Ni-SiO_2-Si structure, electron-hole pairs will be generated in the semiconductor[25]. The electron-hole pairs will separate by the built-in electric field and break the Schottky barrier equilibrium state[3-7]. The electrons will diffuse from the illumination area to the non-illumination area after the electrons enter the metal layer to build a new equilibrium state. Because the distance is different between the two electrodes and the laser irradiation position, the electron concentration difference will be generated at the two electrode points to form LPV, which can be represented by[26]

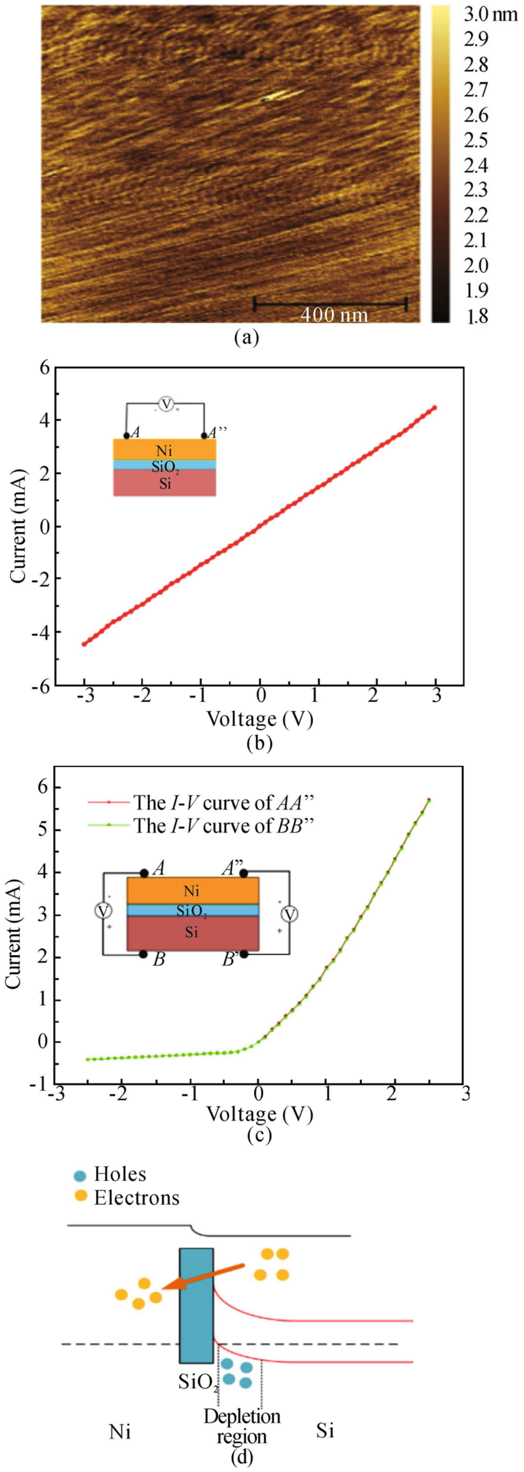


Fig.2 (a) AFM topography of Ni-SiO$_2$-Si structure; (b) Transverse *I-V* curve of Ni-SiO$_2$-Si structure; (c) Vertical *I-V* curve of Ni-SiO$_2$-Si structure; (d) Schematic diagram of energy band in Ni-SiO$_2$-Si structure

$$\mathrm{LPV}=K(N_A-N_B)=2\frac{KPt\lambda\delta_{\mathrm{n}}}{l_0hc}\exp(\frac{-L}{l_0})x,$$

$$-L<x<L, \tag{1}$$

where P is the laser power, t is the irradiation time, λ is the laser wavelength, h is the Planck constant, c is the speed of light, K is the proportional coefficient, l_0 is the electron diffusion length, δ_{n} is the probability of holes entering the metal layer, and L is half the distance between the two electrode points.

As shown in Fig.3(a), the LPE sensitivity varies with laser wavelengths. The LPE sensitivity reaches a maximum of 5.5 mV/mm with 532 nm wavelength and 3 mW laser, while the minimum sensitivity is 2.9 mV/mm with a wavelength of 405 nm. Moreover, the correlation coefficient r reached 0.97, which indicates that the selected electrode distance, laser spot diameter and other factors are set reasonably as shown in Tab.1. There are two main reasons for different sensitivity with laser wavelengths. The first is that sample has optimum absorption rate as shown in Fig.3(b), and more electron-hole pairs can be produced when the sample is irradiated by optimum laser wavelength. The second is penetration depth is different with laser wavelength, electron-hole pairs are generated at different depths within the semiconductor body when laser irradiated on semiconductor, and electron-hole pairs at deeper positions can cause longer transport time for carriers to seek equilibrium states. As shown in Fig.3(c), the LPE sensitivity increases with laser power in a certain range due to higher power lasers can re-excite electron-hole pairs from already recombined state. The LPE sensitivity does not change with the laser power when LPE reaches saturation. The LPE sensitivity saturation value varies with laser wavelengths due to the electrons re-excited opportunities is different by photons. Although photogenerated electron-hole pairs increase with laser power, the number of electrons is limited which can be transported by the built-in electric field. The LPE sensitivity is saturated when the velocity of electron generation is equal to the recombination velocity to reach dynamic equilibrium. LPV shows a positive correlation with the laser power as shown in Eq.(1), which also explains that LPV increases with laser power within a certain range. However, although photogenerated electron-hole pairs can increase with laser power, they are limited to hole transport time by the built-in electric field. Therefore, LPV does not increase with laser power, and it also indirectly proves that LPV mainly comes from electron diffusion rather than thermal effects.

In order to verify the hypothesis that faster response speed can be achieved with bias, transient LPE was measured for comparative experiments without bias. A 532 nm YAG pulse laser was irradiated on Ni-SiO$_2$-Si structure to study transient LPE with power of 3 mW. The transient response of measurement point A is shown in the Fig.4. The transient response of LPE exhibits an exponential increase and relaxation trend, the response time is 450 μs and the relaxation time is 2 250 μs.

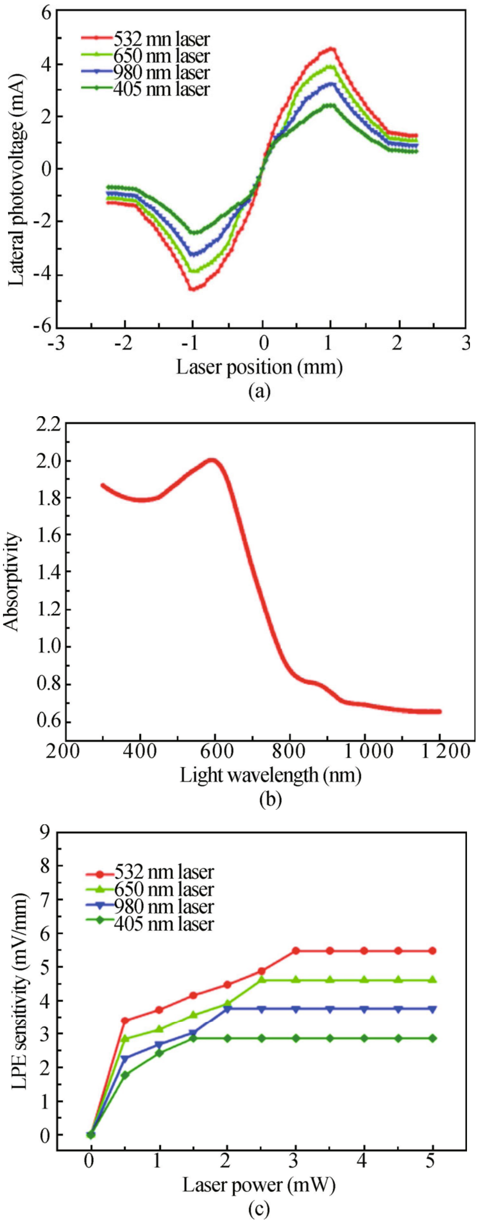


Fig.3 (a) LPE with different laser wavelengths at 3 mW in the Ni-SiO$_2$-Si structure; (b) Absorptivity of the Ni-SiO$_2$-Si structure from 300 nm to 1 200 nm; (c) LPE sensitivity as a function of laser power with different laser wavelengths in the Ni-SiO$_2$-Si structure

Tab.1 Results of LPE with different wavelengths and 3 mW laser power in the Ni-SiO$_2$-Si structure

Wavelength (nm)	Sensitivity (mV/mm)	*R*-square	Pearson's *r*
405	2.9	0.984 83	0.992 58
532	5.5	0.977 13	0.988 79
650	4.6	0.994 38	0.992 36
980	3.8	0.972 05	0.986 28

The Schottky barrier would be enhanced in Ni-SiO$_2$-Si structure with bias, and the Schottky barrier would be strengthened in the part of the range where is centered on the applying bias. Therefore, two types of applying bias modes are designed to study the LPE with bias as shown in Fig.5, respectively. It was called mode 1 (M$_1$) when applying bias to *AB*, and the mode 2 (M$_2$) is bias applying to *A*'*B*'.

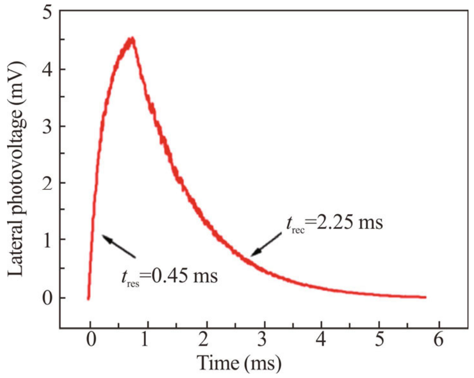


Fig.4 Transient LPE of the Ni-SiO$_2$-Si structure without bias

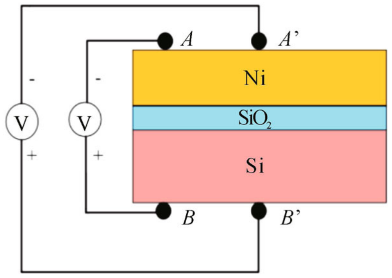


Fig.5 Two modes with applying bias on the Ni-SiO$_2$-Si structure

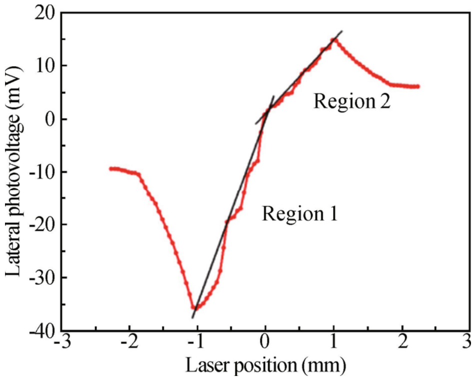
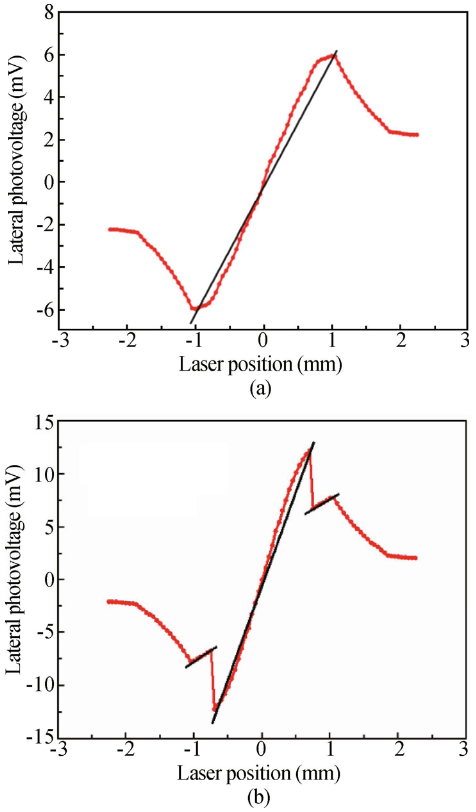


Fig.6 Relationship between LPV and laser irradiation position in the Ni-SiO$_2$-Si structure with −4 V bias

Fig.7 shows the relationship between LPE and laser position with bias in M$_2$. Because the laser scans along the electrode connection direction in actual measurement, the electrode contacts are installed 2 mm above the corresponding electrode points on the backlight side with bias. Since the LPE was measured along the electrode connect line, the LPE component can be ignored which is perpendicular to the electrode line direction. Although the regional boundary is about 0.45 mm according to the previous measurement of M_1 with −1 V bias, there is no obviously nonlinear behavior observed in Fig.7(a). The explanation for the phenomenon is that the bias is small, the LPV amplitude changes lowly caused by Schottky barrier, and the LPV amplitude is larger when the laser irradiation position is near the electrode without bias. Therefore, there is no nonlinearity behavior achieved with −1 V bias. However, there is significant nonlinear behavior when the bias is −2 V and −3 V as shown in Fig.7(b) and (c), and different LPE sensitivities in the three regions can be observed due to the significant amplitude variation of LPV. While the linear relationship was obtained between the two electrodes with bias from −4 V to −7 V as shown in Fig.7(d) and Tab.3. The LPE presents a good linear characteristic from −4 V to −7 V, which is mainly the wide coverage area of high Schottky barrier height caused by high bias. Therefore, the best ways to study LPE is with bias above −4 V in M_2.

Tab.2 LPE regional boundary and sensitivity in the Ni-SiO$_2$-Si structure with different biases

Bias (V)	Regional boundary (mm)	Region 1 sensitivity (mV/mm)	Region 2 sensitivity (mV/mm)
−1	−0.55	8.2	6.3
−2	−0.3	14.2	8.6
−3	−0.1	25.5	10.8
−4	0.1	37.4	14.3
−5	0.2	48.1	21.9
−6	0.4	65.6	35.3
−7	0.5	76.2	45.3



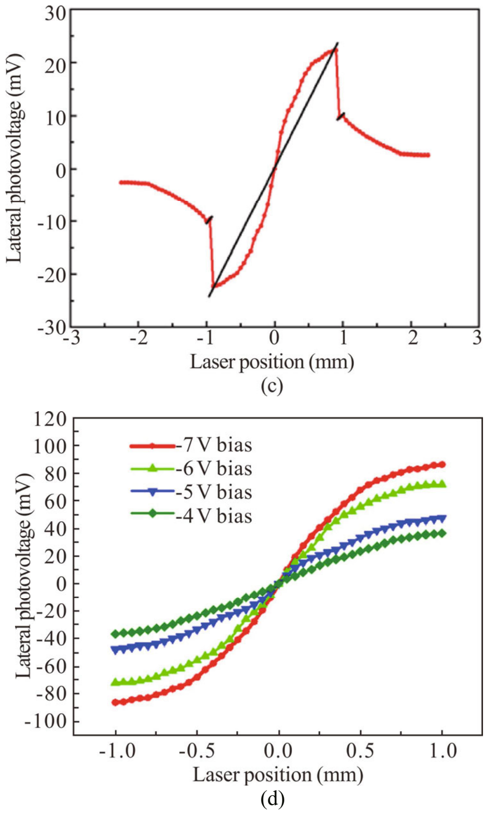


Fig.7 LPE sensitivity and linearity with (a) −1 V bias, (b) −2 V bias, (c) −3 V bias, and (d) swept from −4 V to −7 V bias

Tab.3 LPE linearity and sensitivity swept from −4 V to −7 V bias

Bias (V)	Sensitivity (mV/mm)	*R*-square	Pearson's *r*
−4	42.3	0.989 83	0.995 03
−5	57.1	0.976 79	0.988 62
−6	89.8	0.966 69	0.983 63
−7	107.5	0.965 34	0.982 96

As shown in Fig.7(d), the LPE sensitivity increases with the bias in M_2, which is mainly the increased possibility of the photogenerated holes transmission and reduces the possibility of the tunneling recombination of diffusing holes and electrons. More electron-hole pairs were excited with higher laser power and resulting in greater LPE sensitivity. The LPE with different laser wavelengths and 3 mW laser power in Ni-SiO$_2$-Si structure with −7 V bias is shown in Fig.8. The obtained LPE sensitivity has significantly increased compared to without bias. It is mainly the barrier height increase, which leads to more photogenerated holes entering the metal layer and reduces the recombination rate, resulting in a larger electron concentration and a larger potential difference.

As shown in Fig.9, the LPE sensitivity increases linearly with laser power. The sensitivity can be inferred according to[26]

$$\text{Sensitivity} = 2\frac{K\delta_{\text{n}}Pt\lambda}{l_0 hc}\exp(-\frac{L}{l_0}). \qquad (2)$$

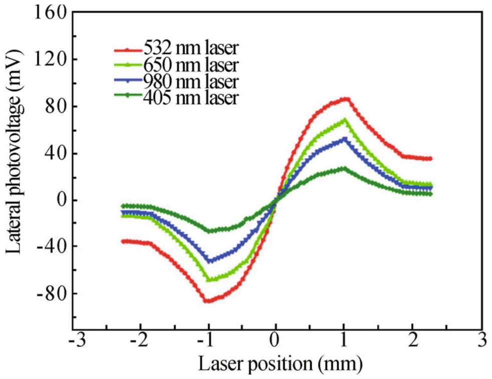


Fig.8 LPE with different laser wavelengths at −7 V bias in the Ni-SiO$_2$-Si structure

Tab.4 LPE sensitivity with different wavelengths at −7 V bias in the Ni-SiO$_2$-Si structure

Laser wavelength (nm)	Sensitivity (mV/mm)	*R*-square	Pearson's *r*
405	32.1	0.979 85	0.990 13
532	107.5	0.965 34	0.982 96
650	83.0	0.972 16	0.986 33
980	61.5	0.981 28	0.990 83

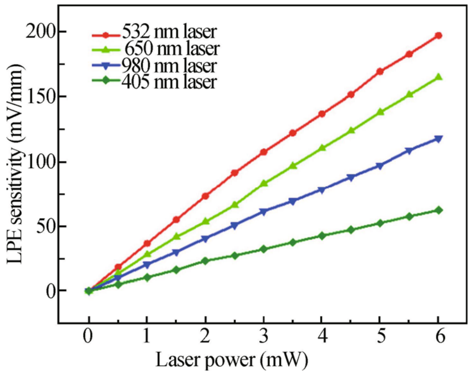


Fig.9 Relationship between LPE sensitivity and laser power with different laser wavelengths at −7 V bias

Some photo-generated holes have the opportunity to enter the metal layer by built-in electric field. Although the number of electron-hole pairs is positively correlated with laser power, the limited number of holes that can enter the metal layer is attributed to the long transportation time and short recombination time. However, Ni-SiO$_2$-Si structure has a larger built-in electric field with bias, which shortens the transportation time of photo-generated holes and reduces the probability of electron recombination, because there are some essential electrons holes recombination, and the probability can be expressed as[26]

$$\delta_{\mathrm{n}} = C[1-\exp(-\frac{E}{E_0})], \qquad (0 < C < 1), \tag{3}$$

where C is a constant, E_0 is an electric field strength constant related to laser power, and E is the electric field strength derived from the original Schottky barrier and bias.

Combining Eqs.(2) and (3), the sensitivity can be expressed as[26]

$$\text{Sensitivity} = 2\frac{KCPt\lambda}{l_0 hc}\exp(-\frac{L}{l_0})\times[1-\exp(-\frac{E}{E_0})]. \tag{4}$$

This formula can effectively indicate that the LPE sensitivity increases with increasing bias voltage. When the bias is high enough, E>>E_0, and Eq.(4) can be expressed as[26]

$$\text{Sensitivity} = 2\frac{KCPt\lambda}{l_0 hc}\exp(-\frac{L}{l_0}), \tag{5}$$

which indicated that all parameters are known except for laser power, so the LPE sensitivity will linearly increase with laser power.

The above research is based on the fact that bias can increase the Schottky barrier which can reduce the recombination probability of electron-hole pairs in Ni-SiO$_2$-Sistructure. LPE sensitivity has gain which is equivalent to increase the concentration of electrons with bias. The electron concentration enhancement indicates that the diffusion speed of electrons would enhance, inevitably. Therefore, a faster response time can be obtained in Ni-SiO$_2$-Si structure. Fig.10 shows that the transient response is with −7 V bias in M$_2$, the response time is 6 μs, and the relaxion time is 47 μs. The response time and relaxion time of LPE with bias from −1 V to −7 V are shown in Tab.5. The LPE response and relaxion time decrease with bias. According to the theory of current continuity equation proposed by NIU et al[19], LPE was determined by the number of electrons flowing into the metal layer per unit area in unit time, and the height of Schottky barrier is positively related to the number of electrons entering the metal layer. Then electrons re-inject into the semiconductor layer to seek recombine with holes to build dynamic balance after electrons entering the metal layer. However, the holes have a possibility to enter the metal layer due to bias increase the Schottky barrier in Ni-SiO$_2$-Si structure. The concentration of electrons increases, resulting in electron diffusion speed having a gain due to the reduction in the number of electrons recombined. Therefore, the response speed of LPE would increase with bias.

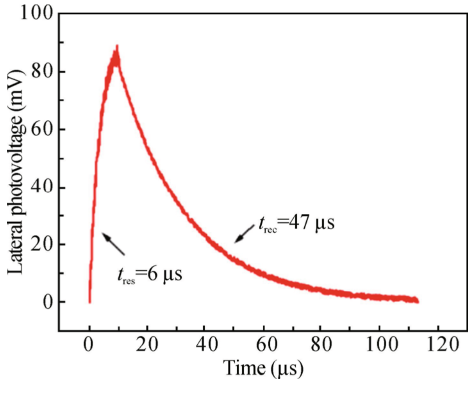


Fig.10 Transient LPE of the Ni-SiO$_2$-Si structure at −7 V bias

Tab.5 Transient LPE of the Ni-SiO_2-Si structure at different biases

Bias (V)	Rise time (μs)	Relaxion time (μs)
-1	219	934
-2	133	567
-3	81	344
-4	49	209
-5	30	127
-6	18	77
-7	6	47

In this paper, LPE was studied in the Ni-SiO_2-Si structure without bias. The Ni-SiO_2-Si structure can obtain prominent LPE sensitivity with 532 nm wavelength and 3 mW power laser. LPE sensitivity increases exponentially with laser power within a certain range without bias, but LPE sensitivity no longer increases with laser power when the LPE sensitivity reaches a certain threshold. The phenomenon proves that the main source of LPE is carrier diffusion rather than thermal effect. The LPE response time can reach 450 μs in Ni-SiO_2-Si structure, and the relaxion time is 2 250 μs. The LPE sensitivity would increase with bias in M_1 significantly, but the LPE linearity is poor with bias swept from −2 V to −3 V. Therefore, we have to artificially divided into two regions and a regional demarcation line to handing data. The regional demarcation line increases with bias, and the LPE sensitivity also increases in the respective region with bias. It is worth noting that the region boundary of LPE is higher than 1 mm when the bias exceeds −4 V. We apply the bias on the position which is 2 mm above the midpoint of the two electrode connections according to this phenomenon. The LPE sensitivity is still poor and even three regions appear when the bias was swept from −2 V to −3 V, while the LPE exhibits good linearity between electrode connection areas when the bias exceeds −4 V. The LPE sensitivity varies with different laser wavelengths with −7 V bias, and the LPE sensitivity with −7 V bias is 19.6 times that without bias. It was found that there is a linear relationship between LPE and laser power with bias. However, there is an exponential relationship between LPE and laser power without bias. Since the bias is much greater than the built-in electric field intensity, the LPE sensitivity is only related to laser power. The Schottky barrier height was enhanced with bias, which results in the enhancement of probability of holes entering the metal layer and reducing the transport time and probability of electron-hole recombination. Therefore, the electron concentration increases with bias, resulting in the LPE sensitivity has a gain. The diffusion speed of electrons also increases with concentration of electrons. LPE response time and relaxation time decrease with diffusion speeds, so the LPE response time decreases with the bias. In conclusion, the LPE response speed and relaxation speed can be improved with bias. This paper introduces a method to improve the LPE sensitivity and response speed in Ni-SiO_2-Si structure with bias. It indicates that the Ni-SiO_2-Si structure is a potential choice to improve the performance of sensors with bias.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

References

[1] SCHOTTKY W. Ueber den entstehungsort der photoelektronen in kupfer-kupferoxydul-photozellen[J]. Physikalische zeitschrif, 1930, 31: 913-925.

[2] WALLMARK J T. A new semiconductor photocell using lateral photoeffect[J]. Proceedings of the IRE, 1957, 45(4): 474-483.

[3] YU C Q, WANG H, XIAO S Q, et al. Direct observation of lateral photovoltaic effect in nano-metal-films[J]. Optics express, 2009, 17(24): 21712-21722.

[4] ZHENG D, DONG X, LU J, et al. High-sensitivity infrared photoelectric detection based on WS_2/Si structure tuned by ferroelectrics[J]. Small, 2022, 18(7): 2105188.

[5] CAO Y, ZHAO Z, BAO P, et al. Lateral photovoltaic effect in silk-protein-based nanocomposite structure for physically transient position-sensitive detectors[J]. Physical review applied, 2021, 15(5): 054011.

[6] HU J, WANG X, LIN L, et al. High-performance self-powered photodetector based on the lateral photovoltaic effect of all-inorganic perovskite $CsPbBr_3$ heterojunctions[J]. ACS applied materials & interfaces, 2022, 15(1): 1505-1512.

[7] MA J, CHEN M, QIAO S, et al. Photovoltaic-pyroelectric coupled effect in Ag_2Se/Si heterojunction for broad-band, ultrafast, self-powered, position-sensitive detectors[J]. ACS photonics, 2022, 9(6): 2160-2169.

[8] ZHENG D, DONG X, LU J, et al. Ultrafast and hypersensitized detection based on van der Waals connection in two-dimensional WS_2/Si structure[J]. Applied surface science, 2022, 574: 151662.

[9] YU C, WANG H. Large lateral photovoltaic effect in metal-(oxide-) semiconductor structures[J]. Sensors, 2010, 10(11): 10155-10180.

[10] XIAO S Q, WANG H, ZHAO Z C, et al. The Co-film-thickness dependent lateral photo effect in Co-SiO_2-Si metal-oxide-semiconductor structures[J]. Optics express, 2008, 16(6): 3798-3806.

[11] YU C Q, WANG H, XIA Y X. Giant lateral photovoltaic effect observed in TiO_2 dusted metal-semiconductor structure of Ti/TiO_2/Si[J]. Applied physics letters, 2009, 95(14): 141112.

[12] CHI L, ZHU P, WANG H, et al. A high sensitivity position-sensitive detector based on Au-SiO_2-Si structure[J]. Journal of optics, 2010, 13(1): 015601.

[13] XIAO S Q, WANG H, YU C Q, et al. A novel position-sensitive detector based on metal-oxide-semiconductor structures of Co-SiO_2-Si[J]. New journal of physics, 2008, 10(3): 033018.

[14] HUANG X, MEI C, HU J, et al. Potential superiority of p-type silicon-based metal-oxide-semiconductor structures over n-type for lateral photovoltaic effects[J]. IEEE electron device letter, 2016, 37(8): 1018-1021.

[15] PISARENKO T A, BALASHEV V V, VIKULOV V A, et al. Comparative study of the lateral photovoltaic effect in Fe_3O_4/SiO_2/n-Si and Fe_3O_4/SiO_2/p-Si structures[J]. Physics of the solid state, 2018, 60: 1316-1322.

[16] ZHOU P, GAN Z, HUANG X, et al. Size-dependent magnetic tuning of lateral photovoltaic effect in nonmagnetic Si-based Schottky junctions[J]. Scientific reports, 2017, 7(1): 46377.

[17] QIAO S, LIU J, LIU Y, et al. Large near-infrared lateral photovoltaic effect of ITO/Si structure observed at low temperature[J]. IEEE transactions on electron devices, 2016, 63(9): 3574-3577.

[18] LIU Y, LIU J, QIAO S, et al. Bias voltage-modulated lateral photovoltaic effect in indium tin oxide (ITO)/Si(n) structure[J]. Materials letters, 2015, 161: 747-750.

[19] ZHOU P, GAN Z, HUANG X, et al. Nonvolatile and tunable switching of lateral photo-voltage triggered by laser and electric pulse in metal dusted metal-oxide-semiconductor structures[J]. Scientific reports, 2016, 6(1): 32015.

[20] WANG W, LI H, LIU X. Hyperdoping-regulated room-temperature NO_2 gas sensing performances of black silicon based on lateral photovoltaic effect[J]. Sensors and actuators B: chemical, 2023, 382: 133473.

[21] HUANG C Y, HE X R, DAI T Y. Realization of a self-powered Cu_2O ozone gas sensor through the lateral photovoltaic effect[J]. Journal of materials chemistry C, 2022, 10(43): 16517-16523.

[22] QIAO S, LIANG B, LIU J, et al. Lateral photovoltaic effect based on novel materials and external modulations[J]. Journal of physics D: applied physics, 2021, 54(15): 153003.

[23] ZHANG B, DU L, WANG H. Bias-assisted improved lateral photovoltaic effect observed in Cu_2O nano-films[J]. Optics express, 2014, 22(2): 1661-1666.

[24] TIAN F, YANG D, OPILA R L, et al. Chemical and electrical passivation of Si (1 1 1) surfaces[J]. Applied surface science, 2012, 258(7): 3019-3026.

[25] SHI X W, XU X J. Detector material and sensitivity analysis for space-based infrared sensors[J]. Optoelectronics letters, 2010, 6: 27-30.

[26] QIAO S, CHEN J, LIU J, et al. Distance-dependent lateral photovoltaic effect in a-Si:H(p)/a-Si:H(i)/c-Si(n) structure[J]. Applied surface science, 2015, 356: 732-736.