The lateral photovoltaic effect in the Ni-SiO_2 -Si structure with bias

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Abstract

We had designed a clamping device to study lateral photovoltaic effect (LPE) in Ni-SiO_2-Si structure due to the appropriate barrier height. We studied LPE with different laser wavelengths and power in Ni-SiO_2-Si structures, the LPE have a prominent sensitivity and linearity. The most suitable laser wavelength is 532nm for studying the LPE in Ni-SiO_2-Si structure, and LPE will increase with the laser power within a certain range and reach the threshold ultimately. The transient response time is 450 μs and the relaxation time is 2250 μs in Ni-SiO_2-Si structure without bias. The LPE sensitivity have a significant improvement with bias. However, the LPE have a poor linearity between two electrodes when bias was applied on electrodes position. We change the bias application method, the linearity and sensitivity of LPE obtained a significant progress when bias was applied in middle of electrodes connection from -4V to -7V. The transient response time is 6 μs and the relaxion time is 47μs with -7V bias. Not only improve the LPE sensitivity but also increase response speed with bias. The research can provide a method for obtaining high sensitivity and response speed based on LPE sensors.

1. Introduction

Since the lateral photovoltaic effect (LPE) was first discovered by W. Schottky in 1930 and then developed by Wallmark in 1957 [1−3]. Researchers mainly conducted research on pn junction [4, 5], metal-semiconductor (MS) [6] 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. [7−10]. 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 which Ti, Co, Ni et al. was fabricated to metal films [6, 7, 11]. High electrical resistivity and a large work function of the metal film in MOS structure would obtain the larger LPE [12]. Currently, almost suitable metals had been studied in MOS structures, researchers had paid their attention to regulate LPE which regulating ways include magnetic field [13], low temperature [14], bias [15] 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. [16], LPE is positively correlated with the number of carriers entering the semiconductor body from the pn junction per unit time 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 contract 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 other micro displacement precision measuring instruments due to the prominent linearity and sensitivity of LPE [6]. The evaluation indicators of LPE include sensitivity and response speed. However, the previous regulation of LPE only involved sensitivity in MOS structure [17], 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 changing the height of the Schottky barrier in Ni-SiO_2-Si structure with bias applying ways.

2. Experiments

The experiments were carried out in the Ni-SiO_2-Si structure, a n-type silicon (Si) (1 1 1) substrate 50-80 Ω·cm was prepared, and the silicon wafer was cut into rectangle of 20×20 mm. The RCA cleaning method was used to clean Si substrates [18]. 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 minutes (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 minutes. And SC-1 and SC-2 would be used repeatedly. The Si wafers then were rinsed under DI water for 30 minutes and subsequently blow dry using N_2 gas at 100 °C for 2 hours. And then they were placed in incubator at 27 °C for 90 days. [4, 5, 19-21] The 4 nm Ni thin films were prepared by DC magnetron sputtering to coated on the Si substrate with 1.2 nm 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 Figure 1(a), laser spot size was controlled at 60 μm, A, A', A', B, B', B" are electrodes point, the A A"=BB" =2mm. We had designed a Ni-SiO_2-Si structure clamping device which can change bias application method as shown in Figure 1(b). Eight fixed needles are used to fix the Ni-SiO_2-Si structure, six spring needles are fixed to contract to Ni-SiO_2-Si structure which was used to measure LPE and apply bias, the material of the spring needles is copper plated gold, and the diameter of spring needle is 0.38mm. 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, the LPE on the back side is slightly smaller than that the illumination side (Ni side), generally [6]. 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 2mm above the corresponding electrode points on the backlight side as shown in Figure 1(c). The laser power was controlled by polarizer and small hole and which was detected by a power meter. The voltage source was used and I-V curve are measured by Keithley 2401 source meters. A pulse width of 50 ms and 500MHz 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.

3. Results and discussion

3.1 Transverse I-V curve and vertical I-V curve in Ni-SiO_2-Si structure

The atomic force microscope (AFM) topography of Ni-SiO_2-Si structure as shown in Figure 2(a), RMS=208.6pm the RMS value indicates surface is flat relatively. The transverse I-V curve of Ni-SiO_2-Si structure shows that have good ohmic contact between electrodes and the metal film as shown in Figure 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 is shown in the Figure 2(c). The barrier structure of the Ni-SiO_2-Si structure is shown in the Figure 2(d) according to the vertical I-V characteristics 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.

3.2 LPE mechanism in MOS 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. The electron-hole pairs will separate by the built-in electric field and breaking 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, LPV can be represented by the formula (3-1) [22]:

$$LPV=K(N_A\text{-}N_B) = 2\frac{K\delta_n}{l_0}\, exp\left(-\frac{L}{l_0}\right)x \text{ -}L<x<L \qquad (3\text{-}1)$$

Where, $n=pt\lambda/(hc)$, p is the laser power, t is the irradiation time, λ is the wavelength, k is the proportional coefficient, and l_0 is the electron diffusion length, δ_n is the probability of holes entering the metal layer, L is half the distance between the two electrode points, h is the Planck constant, and c is the speed of light.

3.3 LPE with laser power and wavelength in Ni-SiO_2-Si structure

As shown in Figure 3(a), the LPE sensitivity varies with laser wavelengths. The LPE sensitivity reaches a maximum of 5.5 mV/mm with 532nm wavelength and 3mW laser, while the minimum sensitivity is 2.9 mV/mm with a wavelength of 405nm. Moreover, the correlation coefficient *r* reached 0.97 which indicating that the selected electrode distance, laser spot diameter and other factors are set reasonably as shown in the Table 1. There are two main reasons for different sensitivity with laser wavelengths, the first is sample has optimum absorption rate as shown in Figure 3(b), the 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 wavelengths, electron-hole pairs are generated at different depths within the semiconductor body when laser irradiated on semiconductor, electron-hole pairs at deeper positions can cause longer transport times for carriers to seek equilibrium states. As shown in Figure 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 the formula (3-1), 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 unlimited with laser power, it also indirectly proves that LPV mainly comes from electron diffusion rather than thermal effects.

Table.1 The results of LPE with different wavelength and 3mW laser in Ni-SiO_2-Si structure.

Wavelength(nm)	Sensitivity(mV/mm)	Adj. R-Square	Pearson's r
405	2.9	0.98483	0.99258
532	5.5	0.97713	0.98879
650	4.6	0.99438	0.99236
980	3.8	0.97205	0.98628

3.4 Transient LPE in Ni-SiO_2-Si structure

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 532nm YAG pulse laser irradiated on Ni-SiO_2-Si structure to study transient LPE with power of 3mW and laser spot size controlled at 60 μm. The transient response of measurement point A is shown in the Figure 4. The transient response of LPE exhibits an exponential increase and relaxation trend, the response time is 450 μs and the relaxation time is 2250 μs.

3.5 LPE in Ni-SiO_2-Si structure with bias

3.5.1 Different LPE studying mode with bias in Ni-SiO_2-Si structure

The Schottky barrier would be enhance with bias in Ni-SiO_2-Si structure, 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 the Figure 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'.

The Figure 6 shows the relationship between LPE and the laser irradiation position when the bias is -4V in Mode 1. Because the interference from the clamping device, the LPV on the left side of electrode A cannot be measured. The LPE linearity is poor between two electrodes, so LPE is artificially divided into two linear regions between the two electrodes area and the region boundary is specified. The LPE sensitivity is 37.4 mV/mm in region 1, and the LPE sensitivity is 14.3 mV/mm in region 2. LPE exhibits greater sensitivity when the laser irradiation position is near electrode point A (referred to region 1). The explanation for this phenomenon is that although bias increases the height of the Schottky barrier and increases the probability of photogenerated holes entering the metal layer, the Schottky barrier formed is not uniform with bias. Therefore, the LPE sensitivity of the linearity region near the electrode A is higher than of that the linearity region far from the electrode A (referred to region 2). The LPE sensitivity of region 2 is less than that of region 1, since region 2 is faint influenced which compare to region 1 by the change of Schottky barrier in M_1. The regional boundary and the LPE sensitivity from -1 V to -7 V bias of the two regions is shown in the Table 2. The calculated sensitivity of each region was fitted by Origin software. The LPE regional boundary and the sensitivity increase with bias. Moreover, the region boundary exceeds the midpoint of the two electrodes connection when the bias reaches -4V.

Table 2. The LPE regional boundary and sensitivity in Ni-SiO_2-Si structure with different bias.

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

The Figure 7 shows the relationship between LPE and laser position with bias in M_2. Because the laser scan along the electrode connection direction in actual measurement, the electrode contacts are installed 2mm above the corresponding electrode points on the backlight side to apply bias. Since the LPE was measured along the electrode connect line, the LPE component can be ignored which perpendicular to the electrode line direction. Although the regional boundary is about 0.45mm according to the previous measurement of M_1 with -1V bias, there are not obviously nonlinear behavior was observed in the Figure 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 near the electrode without bias. Therefore, there are no any nonlinearity behavior was achieved with -1V bias. However, there are significant nonlinear behavior when the bias is -2V and -3V as shown in Figure 7(b) and 7(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 -4V to -7V is shown in the Figure 7(d) and Table 3. The LPE presents a good linear characteristic from - 4V to -7V, which is mainly the wide coverage area of high Schottky barrier height caused by high bias. Therefore, the best ways to study LPE with bias above -4V in M_2.

Table 3. The LPE linearity and sensitivity from -4V to -7V bias.

Bias (V)	Sensitivity (mV/mm)	Adj. R-Square	Pearson's r
-4	42.3	0.98983	0.99503
-5	57.1	0.97679	0.98862
-6	89.8	0.96669	0.98363
-7	107.5	0.96534	0.98296

3.5.2 The LPE sensitivity with laser wavelength and power in Ni-SiO_2-Si structure with bias

As shown in Figure 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 diffuse 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 3mW laser power in Ni-SiO_2-Si structure with -7V bias as shown in Figure 8. The obtained LPE sensitivity has significantly increased compared to without bias. It is mainly the barrier height increase which leads to more photo-generated holes entering the metal layer and reduces the recombination rate resulting in a larger electron concentration and a larger potential difference.

Table 4. LPE sensitivity with different wavelengths in Ni-SiO_2-Si structure with -7V bias

Laser wavelength(nm)	Sensitivity (mV/mm)	Adj. R-Square	Pearson's r
405	32.1	0.97985	0.99013
532	107.5	0.96534	0.98296
650	83.0	0.97216	0.98633
980	61.5	0.98128	0.99083

As shown in Figure 9, the LPE sensitivity increases linearly with laser power. The sensitivity can be inferred according to formula (3-1) [22]:

$$Sensitivity=2\frac{K\delta_n}{l_0}exp\left(-\frac{L}{l_0}\right) \tag{3-2}$$

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 have 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, the probability can be expressed as [22]:

$$\sigma=C\left[1-exp\left(-\frac{E}{E_0}\right)\right](0<C<1) \tag{3-3}$$

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 formulas (3-2) and (3-3), the sensitivity can be expressed as [22]:

$$Sensitivity=2\frac{KCPt\lambda}{l_0hc}exp\left(-\frac{L}{l_0}\right) \times\left[1-exp\left(-\frac{E}{E_0}\right)\right] \tag{3-4}$$

This formula can effectively indicate that the LPE sensitivity increases with increasing bias voltage.

When the bias is high enough, E>>E0, formulas (3-4) can be expressed as [22]:

$$Sensitivity=2\frac{KCPt\lambda}{l_0hc}exp\left(-\frac{L}{l_0}\right) \tag{3-5}$$

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

3.5.3 LPE transient response in Ni-SiO_2-Si structure with bias

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-Si structure. 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. The Figure 10 shows that the transient response with -7V bias in M_2, the response time is 6 μs, and the relaxion time is 47μs. The response time and relaxion time of LPE with bias from -1V to -7V are shown in the Table 5. The LPE response and relaxion time decrease with bias. According to the theory of current continuity equation proposed by Niu et al.[16], 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 which 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 have a gain due to the reduction in the number of electrons recombined. Therefore, the response speed of LPE will increase with bias.

Table 5. The transient LPE of Ni-SiO_2-Si structure with different bias.

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

4. Conclusion

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 532nm 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, the relaxion time is 2250 μs. The LPE sensitivity would improve with bias in M_1 significantly, bur the LPE linearity is poor with bias from − 2V to -3V. Therefore, we have to artificially divided into two regions and a regional demarcation line to handing data. The regional dividing 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 1mm when the bias exceeds − 4V. We apply the bias on the position which is 2mm 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 − 1V to -3V, while the LPE exhibits good linearity between electrode connection area when the bias exceed − 4V. The LPE sensitivity varies with different laser wavelengths with − 7V bias, and the LPE sensitivity with − 7V bias is 19.6 times than 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, and the LPE sensitivity is only related to laser power. Since the Schottky barrier height was enhanced with bias resulting 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 LPE sensitivity have 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 which applying bias to improve the response speed in Ni-SiO_2-Si structure.

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Figures

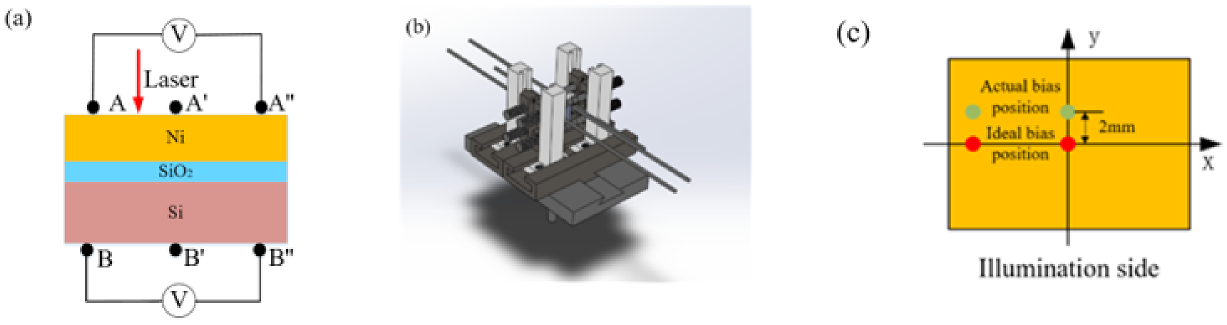

Figure 1

(a). The schematic diagram of LPE in Ni-SiO_2-Si structure.

(b). The isometric drawing of clamping parts.

(c). The schematic diagram of the bias application position in Ni-SiO_2-Si structure.

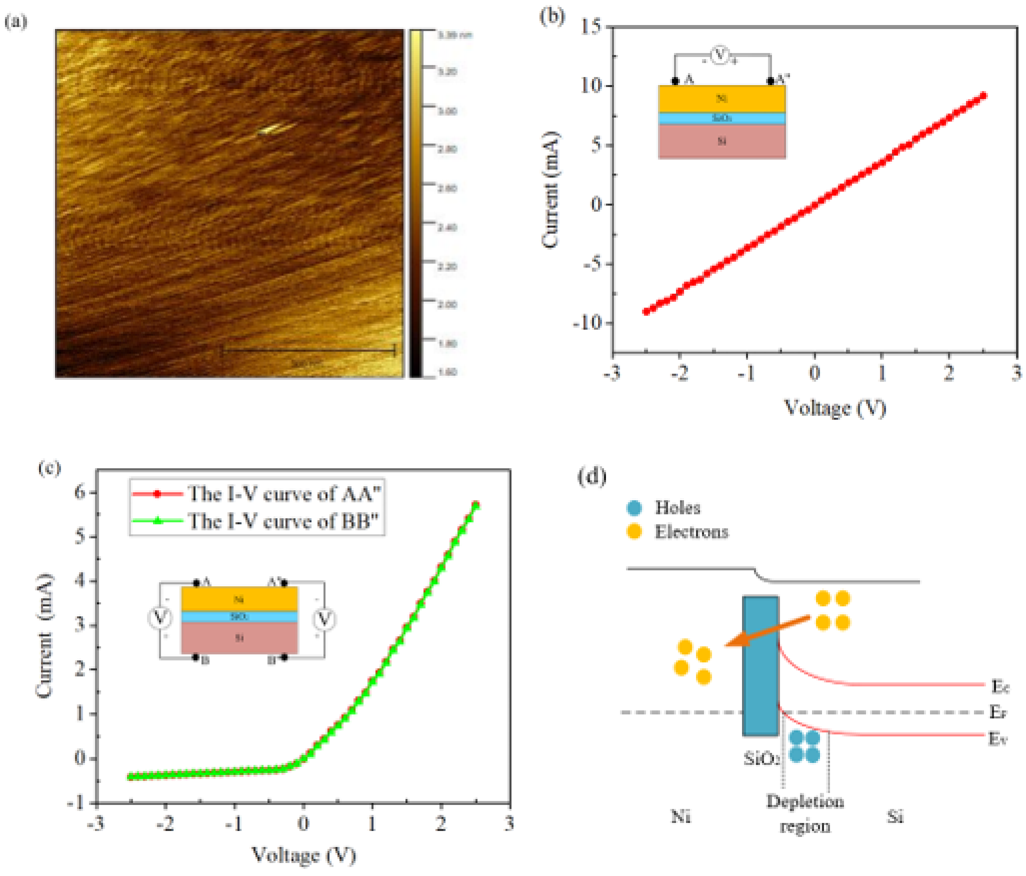

Figure 2

(a). The atomic force microscope (AFM) topography of Ni-SiO_2-Si structure.

(b). The transverse I-V curve of Ni-SiO_2-Si structure. (c). The vertical I-V curve of Ni-SiO_2-Si structure. (d). The schematic diagram of energy band in Ni-SiO_2-Si structure.

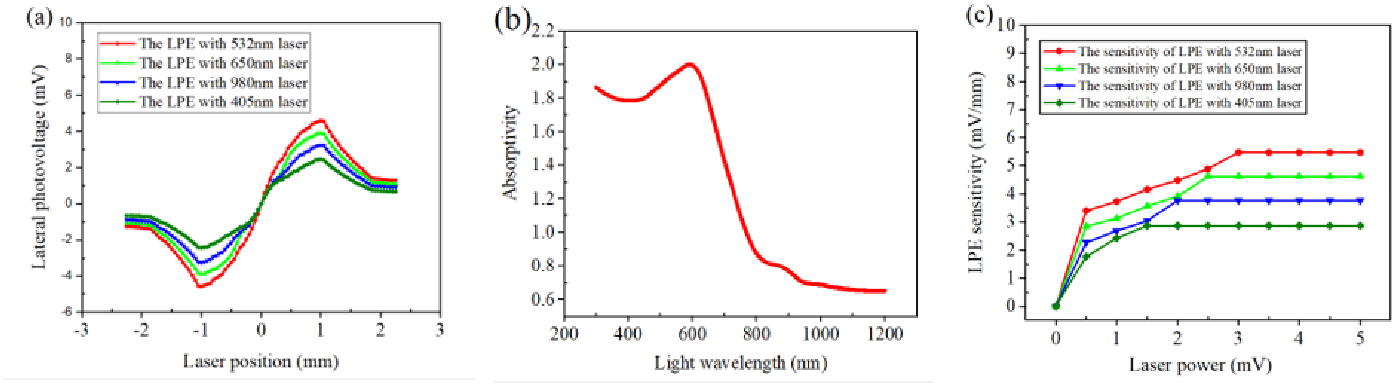

Figure 3

(a). LPE have a dependence with laser wavelengths at 3 mW in Ni-SiO_2-Si structure. (b). LPE have a function with laser power and different laser wavelength in Ni-SiO_2-Si structure. (c). The absorptivity of Ni-SiO_2-Si structure from 300nm to 1200nm.

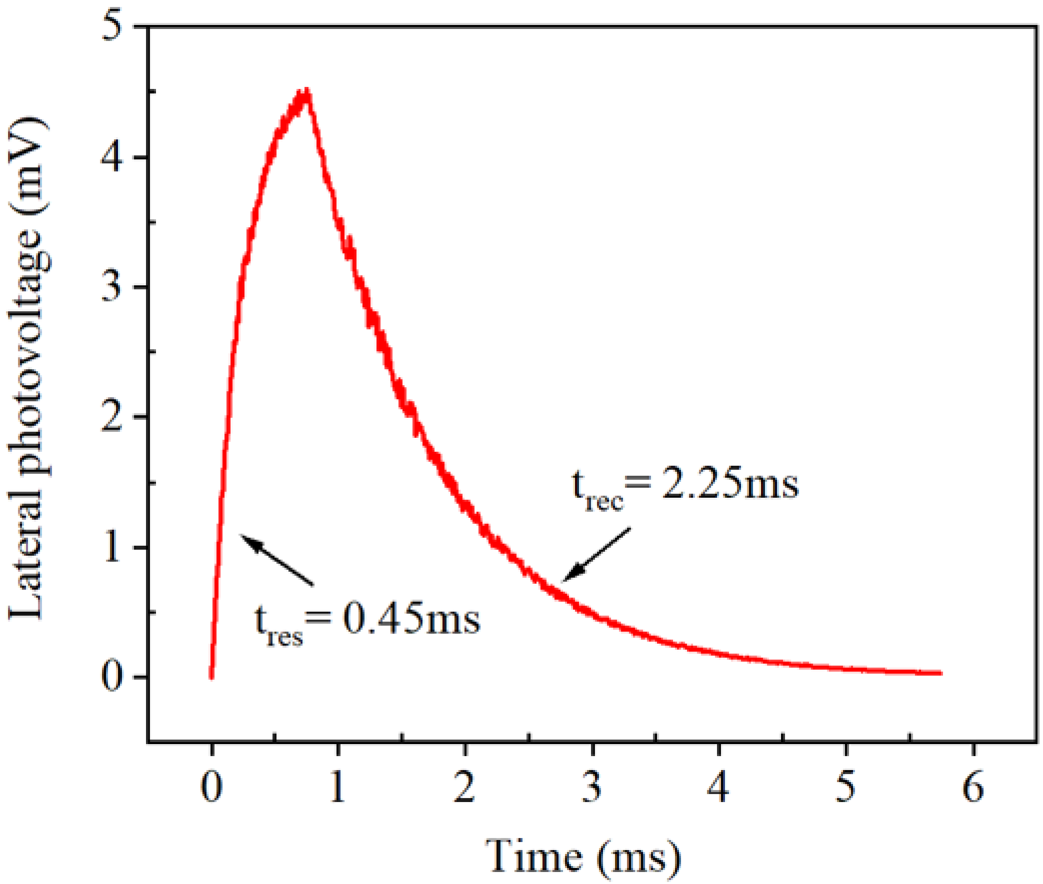

Figure 4

The transient LPE of Ni-SiO_2-Si structure without bias.

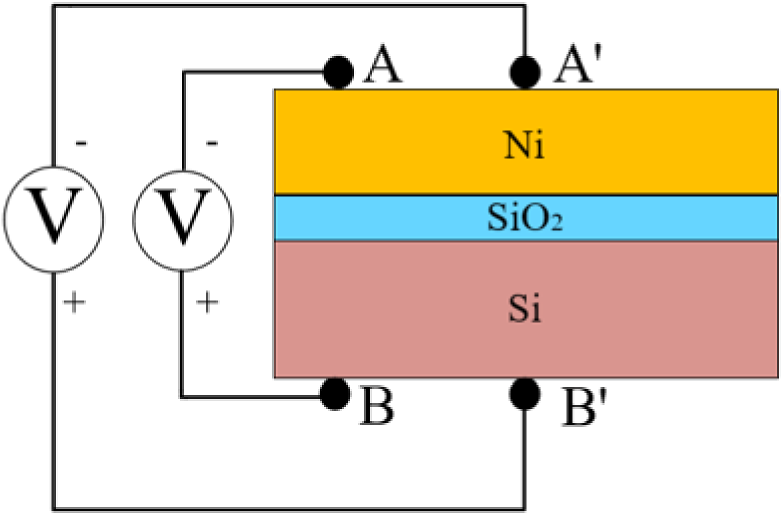

Figure 5

Two modes with applying bias to Ni-SiO_2-Si structure.

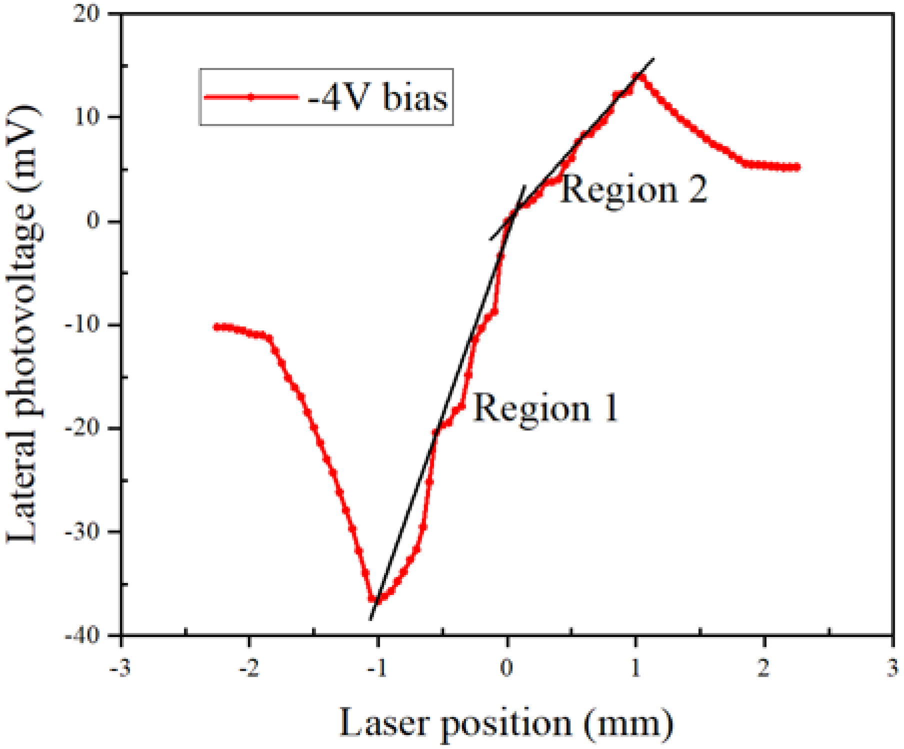

Figure 6

The relationship between LPV and laser irradiation position in Ni-SiO_2-Si structure with -4V bias.

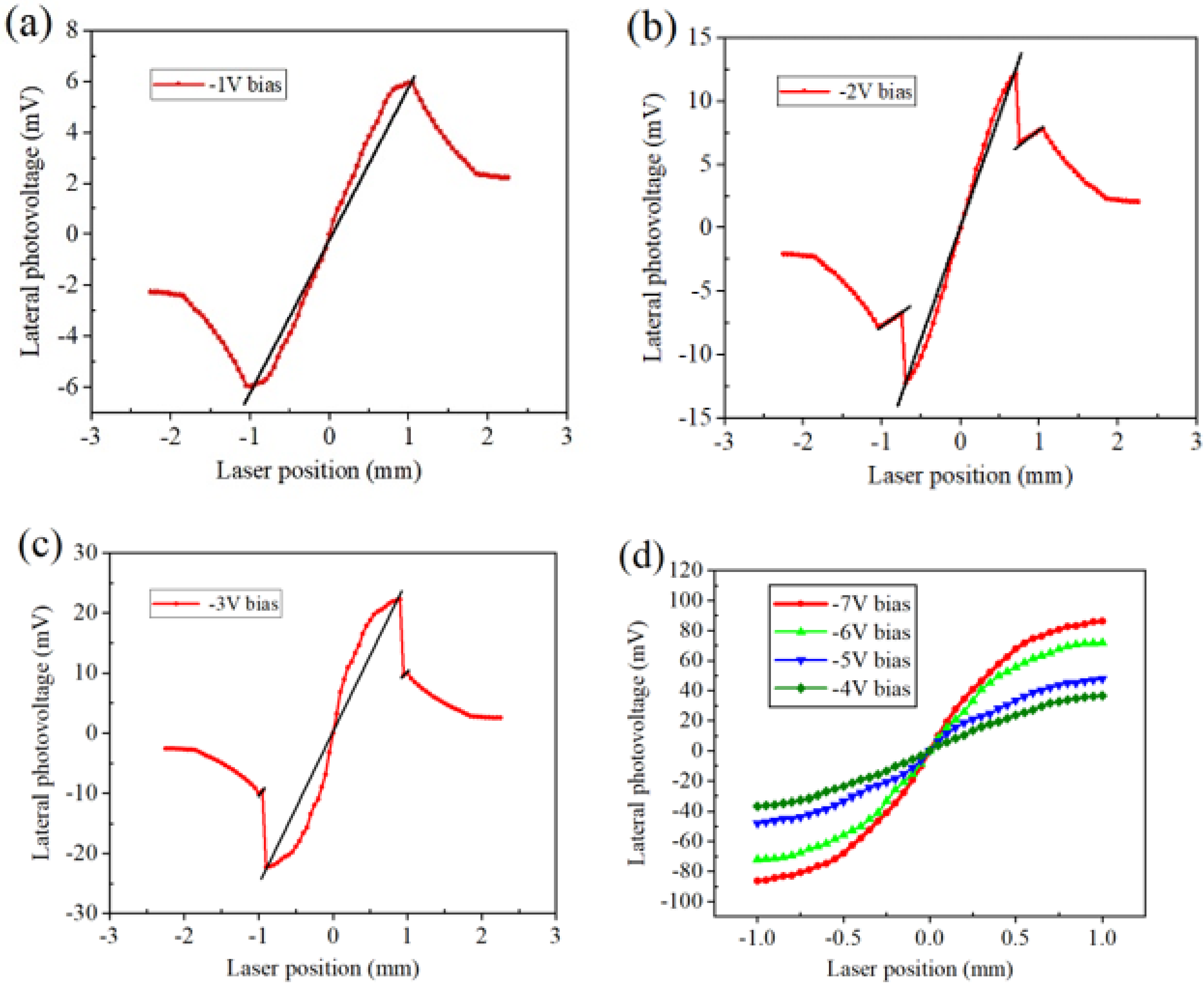

Figure 7

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

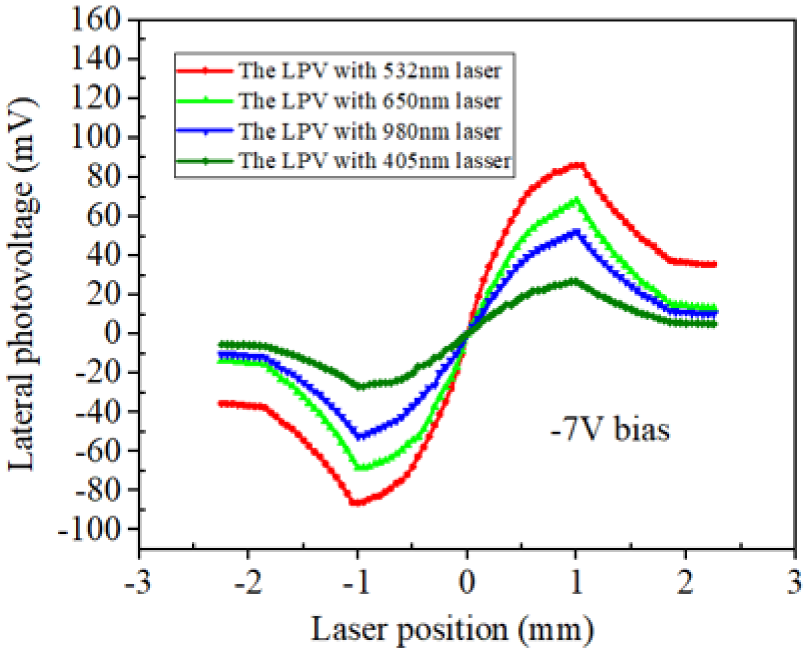

Figure 8

The LPE have a dependence with laser position with different wavelengths with -7V bias in Ni-SiO_2-Si structure.

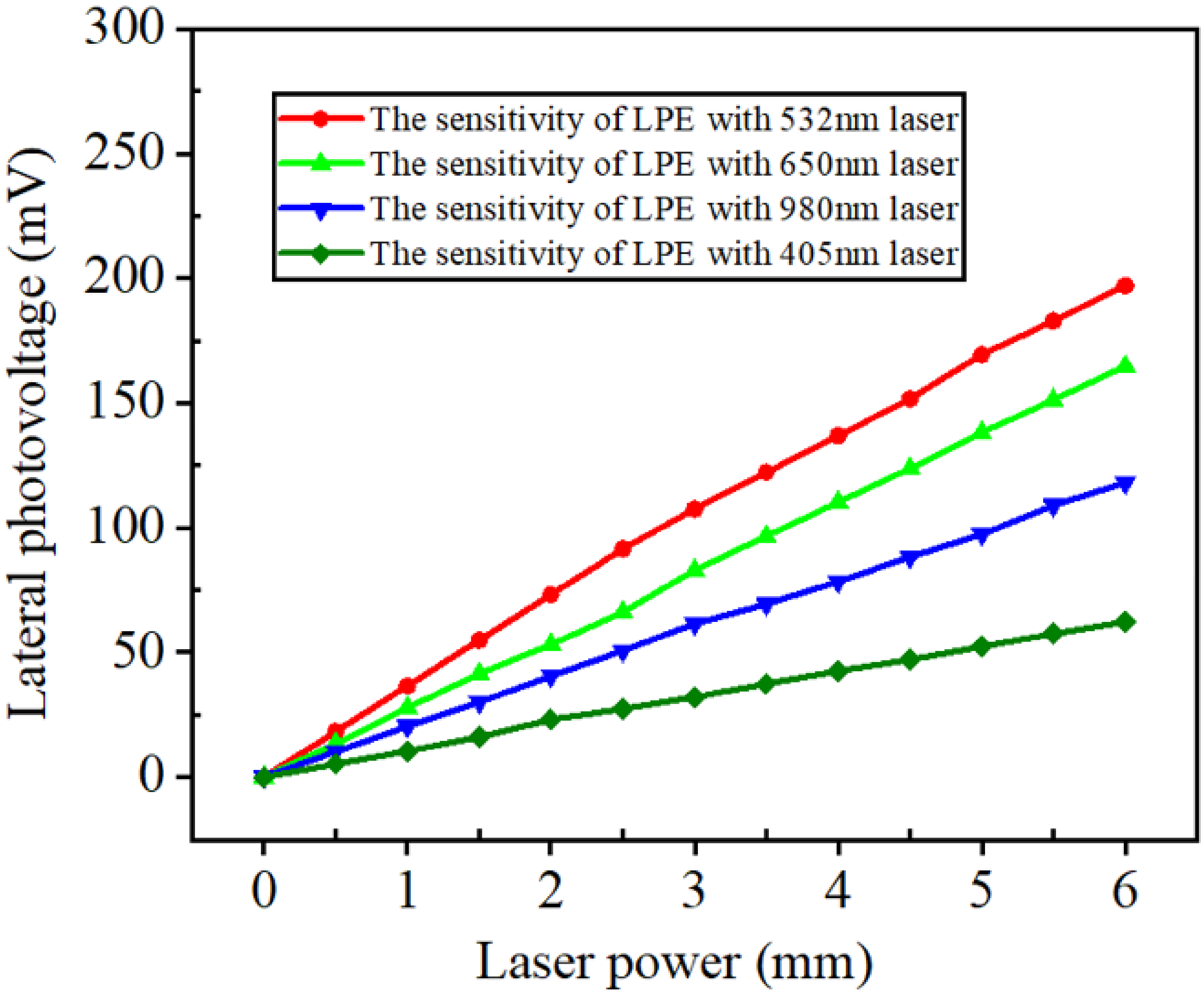

Figure 9

The relationship between LPE and laser power with different laser wavelength with -7V bias.

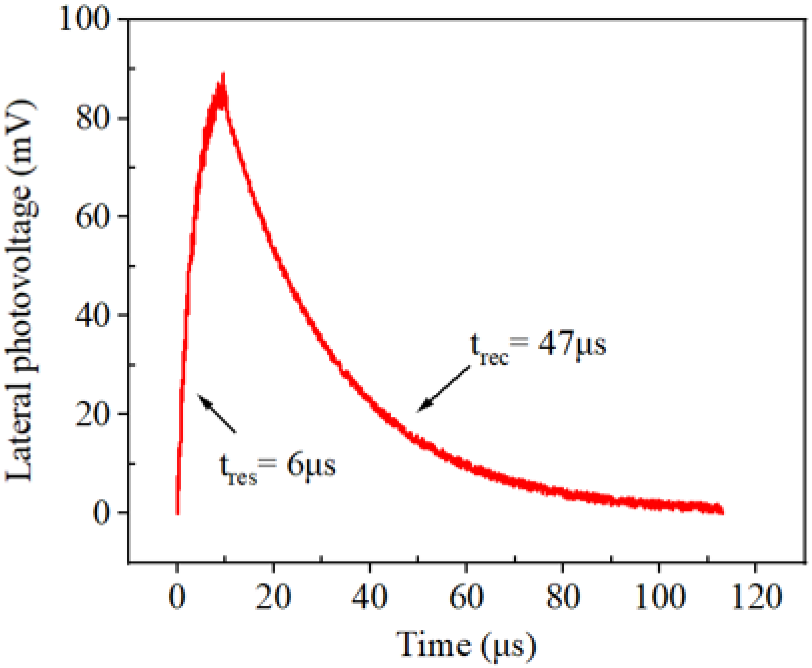

Figure 10

The transient LPE of Ni-SiO_2-Si structure with -7V bias.