Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

A New OEW Microfluidic Device based on p-n Junction*

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***Abstract*—Compared with the electrowetting on dielectric (EWOD) microfluidic device, optoelectrowetting (OEW) microfluidic device does not need to control the on-off of single electrode, but only needs to change the lighting condition to control the droplet, simplifying the peripheral control device and improving the stability of the device. The contradiction between the operating voltage and the driving force exists in the existing OEW device. To solve this problem, this paper proposes an OEW device based on diode structure, which uses the photoelectric effect of the diode connected in the DC circuit to control the movement state of the droplet. In this paper, the feasibility of the OEW device with pn structure is theoretically analyzed. Compared with the previous OEW device, under the same applied voltage and the same illumination difference, the potential difference between the diodes in the new device will be significantly larger than the potential difference between the photoresistors, which will effectively improve the driving force of the DC drive.**

Key words — microfluidic; opto-electrowetting; Optical actuation of microfluid.

I. Introduction

Electrowetting on dielectric (EWOD) drive has attracted the attention of most researchers in the field of digital microfluidic due to its ability to process discrete droplets in parallel and its advantages of no requirement on the target droplets. In the past 20 years, there have been a lot of studies on the drive principle, manufacturing process and chip design, and good results have been achieved. However, EWOD has some unavoidable limitations due to its driving principle: one-dimensional linear electrode array limits the ability of sequential processing, and two-dimensional electrode array has some problems such as complex wiring and addressing difficulties. At the same time, with the device and liquid drops becoming smaller and smaller, the requirements on processing technology and peripheral equipment are also becoming higher and higher, which is difficult to be widely popularized and used [1][2].Therefore, in recent years, many new driving methods have been studied, such as magnetic driving, thermal capillary force driving, sound wave driving, optical driving and so on. Among them, optical drive mode is safe and easy to get, no wiring, no addressing, simple peripheral, and has good biological compatibility, can achieve contactless operation, is an ideal driving mode. A lot of researches have been done on optical drive microfluidic, including radiation pressure, optical tweezers, photoinduced capillary force, photothermal capillary effect and other optical drive mechanisms. Compared with electric drive, these optical drive mechanisms have low driving force and great practical application limitations [3-9].

In 2003, Chiou et al. at the university of California, California, first proposed the concept of optoelectrowetting (OEW) : adding a photosensitive material layer under the electrode array of the traditional EWOD microfluidic device, and changing the light condition to change the conductive property of the photosensitive material, so as to realize the light-controlled electric drive of liquid drops. They succeeded in changing the contact Angle of 30°by irradiating a beam of 65mV/cm^2 with 100V, 500Hz alternating current and using a 4mv laser beam to transport a microliter of deionized water droplets at a speed of 7mm/s [10]. In 2008, Chiou et al. changed the chip structure design and successfully transported 100nL droplets at a speed of 78mm/s under 100V and 500Hz alternating current with a beam of intensity of 5mV/cm^2, realizing the generation, transportation and separation of smaller droplets on the OEW device and parallel operation of multiple droplets [11].In the same year, they also reported a continuous photoelectric wetting mechanism, giving up the patterned electrode scheme and relying on the spot size and configuration to complete the driving of liquid droplets, further simplifying the chip manufacturing process and realizing smaller operation [12]. Chiou et al., university of California, USA and Chuang et al., Purdue university, USA reported the open single-sided OEW device in 2010 and 2008 respectively [13][14]. In 2018, Park et al. at the national university of Singapore made a portable photoelectric wetting device with a single-side OEW device, which could realize rapid on-site water quality detection [15].

II. OEW MICROFLUIDIC DRIVE

A. OEW microfluidic drive principle

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon}{2d\gamma_{LG}}V^2 \quad (1)$$

Formula (1) is young-Lippmann equation [16], θ is the contact Angle, θ_0 is the initial contact Angle, ε is the dielectric constant of the dielectric layer, d is the thickness of the dielectric layer, γ_{LG} is the surface tension of the gas-liquid interface, V is the driving voltage. Contact angle is used to measure the parameters of the material surface hydrophobicity, the contact Angle is a parameter used to measure the

* Authors acknowledge financial support from National Key R&D Program of China (2018YFB1304905) and Natural Science Foundation of Jiangsu Province of China (BK20171215).

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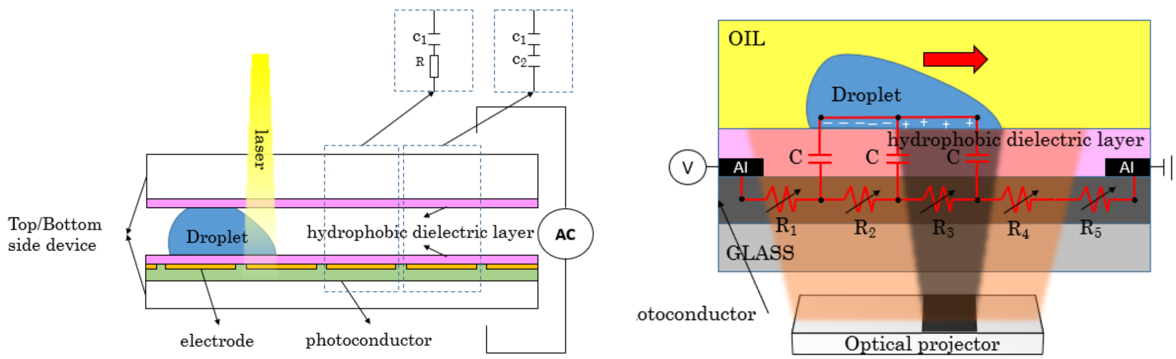

(a) (b)

Fig.1.Structure diagram of two OEW devices

hydrophobicity of the material surface. The change value of the contact Angle has the greatest correlation with the driving voltage. The EWOD device controls the voltage difference between the adjacent electrodes, causing a difference in hydrophobicity on the corresponding surface, and drives the droplet movement, so that each electrode needs to be connected to the peripheral control device by wire connection. Fig.1 shows a schematic diagram of the two OEW devices, which differ in electrode structure, lighting requirements, and driving voltage. The device in Fig.1(a) uses alternating current and bright spot movement to drive and control the droplet. Under the electrode irradiated by light, the conductive property of the photosensitive material is enhanced, the main voltage drop is transferred from the photosensitive material layer to the corresponding dielectric layer, and the corresponding surface becomes more hydrophilic, making the liquid drop move towards the part with light. The device in Fig.1(b) uses direct current and dark band movement to realize droplet drive and control. The electrical conductivity of the photosensitive material in the part without light is lower than that in the part with light. Therefore, the voltage applied horizontally in the photosensitive layer mostly falls in the area without light, and the corresponding surface is more hydrophilic, and the droplet moves towards the part without light.

B. *Advantages and disadvantages of OEW microfluidic device at present*

Compared with the EWOD microfluidic device, the above two OEW microfluidic devices do not need to control the power supply on and off of the electrode, but change the pressure drop difference of the adjacent (virtual) electrode through the change of the lighting condition, which simplifies the peripheral control device and improves the stability of the device. However, the device in Fig.1(a) is relatively high voltage and high frequency alternating current, which is not conducive to the portable improvement of subsequent devices. The device in Fig.1(a) has a relatively weak driving force, which can be seen in the figure to drive the droplets in the silicone oil. The two OEW microfluidic devices have the problems of high driving voltage and weak driving force respectively.

C. *New OEW device based on photodiode structure*

In order to solve the contradiction between working voltage and driving force, this paper presents an OEW device based on p-n junction. The movement of the droplet is controlled by the photoelectric effect of the diode in the dc circuit. According to formula (1), the contact change of the droplet is related to the voltage. The larger the contact Angle difference between the two sides of the droplet, the easier it is for the droplet to be driven. On the basis of the principle of p-n junction inference p-n junction with the change of light intensity changes on both ends of the voltage drop, the analysis of the use of p-n junction in OEW microfluidic device structure can increase the driving force of the dc drive, through the experiment measurement verifies the correctness of theoretical analysis, the final design a OEW device based on the structure of p-n junction and experiment.

III. DRIVING MECHANISM OF NEW OEW DEVICE BASED ON PHOTODIODE STRUCTURE

A. *Basic theoretical analysis of p-n junction*

Photodiode is mainly applied in photoelectric detector. The research focus is on the change of its output current with light intensity. When applying photodiode to OEW device, the relationship between the electric potential difference at both ends and light intensity should be studied. In this paper, the working mechanism of p-n junction is analyzed from the perspective of output voltage. Fig.2 shows the basic structure of the prototype homogeneous p-n junction. The expressions of junction voltage, junction width and current are as follows:

$$\mathrm{V}_j = V_{bi} + V \tag{2}$$

$$\mathrm{w} = \left[\frac{2\varepsilon V_j(N'_A+N'_D)}{qN'_A N'_D}\right]^{1/2} \tag{3}$$

$$\mathrm{I} = I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{4}$$

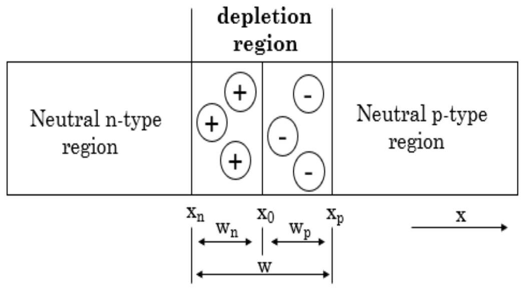

Fig. 2. Schematic diagram of prototype homogeneous p-n junction structure

N_D' and N_A' are the net doping concentration of electrons and holes, respectively, V and V_{bi} are the voltage drop of the applied voltage and the built-in electric field, respectively, I_0 is the reverse saturation current, ε is the dielectric constant, q is the electron charge, n is the quality factor of the diode, k is the boltzmann constant, T is the absolute temperature.

In the equilibrium state (no applied electric field), when the diffusion motion caused by the difference in electron concentration and the drift motion caused by the electric field reach an equilibrium, a pn junction and a stable built-in electric field are formed at the interface. Due to the existence of the built-in electric field, there are almost no free carriers in the junction area. Therefore, this area is also called depletion area. The resistance of depletion area is much higher than that of the other two areas. When there is an applied voltage$V$, the voltage falls almost entirely in the depletion region. According to equations (2) and (3), when the applied reverse bias voltage (the same direction as the built in electric field) is applied, the junction voltage increases, making the electric field intensity and width w in the depletion region increase, and it is more difficult for multiple components to pass through the barrier to generate current, and only a small reverse saturation current I_0 is generated by a small number of components. This working state is usually referred to as the reverse cut-off of the diode.

For semiconductor materials, free electrons are generated when the energy of the photon irradiated is greater than the bandgap width of the semiconductor material. Therefore, when the light that meets the requirements is irradiated onto the pn junction in the dc circuit, free electrons will be generated inside, that is, the concentration of carriers in the depletion area will increase, and these carriers will move from the p-type side to the n-type side under the action of junction electric field, generate reverse current through the external circuit, and the reverse saturation current I_0 will increase [17].

B. *Working mechanism analysis of reverse series p-n junction*

Fig.3 is a schematic diagram of the volt-ampere characteristic curve of photodiode with the change of light intensity drawn according to formula (4).Combined with the above analysis and Fig.3, the voltage at both ends of the p-n junction changes with light conditions when the p-n junction is in reverse series in the dc circuit. Take the reverse series connection of two p-n junctions M and N as an example (power voltage V_O): when the light intensity is A, both p-n junctions

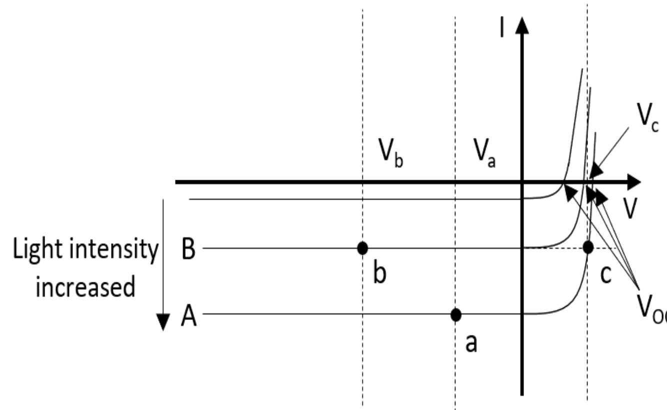

Fig.3. I-V characteristic curves of photodiode under different illumination condition (The ratio of forward and backward voltages is different, and the reverse scale is smaller)

work at point A with the same junction voltage, $V_{JM}=V_{JN}=V_a+V_{OCA}=V_O/2+V_{OCA}$. When the light intensity of p-n junction M changes to B and the light intensity of p-n junction N remains unchanged, because the current in the series circuit is the same, the working point of p-n junction N shifts to c, junction voltage $V_{JN}=V_c+V_{OCA}$, and the working point of p-n junction M shifts to B, junction voltage $V_{JM}=V_b+V_{OCB}$. Because the open circuit voltage is much smaller than the supply voltage, it can be ignored.

IV. DESIGN OF NEW OPTOELECTROWETTING DRIVE

In this paper, an OEW microfluidic device based on diode structure is proposed. It is divided into two device design schemes according to the direction of pn junction. The surface potential and electric f field distribution of the two structures are simulated by COMSOL Multiphysics simulation software. The simulation uses a prototype homogenous pn junction model, that is, the doping impurity is completely ionized and the net doping concentration on both sides of the junction is abrupt, and the p-type and n-type doping concentrations are both $1*10^{15}$ cm^{-3}. At the same time, combined with the results of electrical circuit analysis and test experiments on silicon photodiodes, and because the device uses DC drive, the effect of junction capacitance is ignored, and only the value of junction resistance changes before and after illumination. The default three pn junction models are identical, and the initial condition is that there is illumination. The front and back lighting conditions change the middle model, that is, the intermediate model changes from light to no light, and the junction resistance increases relatively.

The first solution is to place the pn junction horizontally in the device, with the p-side or n-type side acting as the drive surface. According to Fig.4(a), the photodiode is reversely connected in series in the circuit. When all the photodiodes are illuminated, the potential difference between the working faces of the respective pn junctions is the same, and the hydrophobicity of the corresponding surface is the same. When one of them is not illuminated, the applied potential is

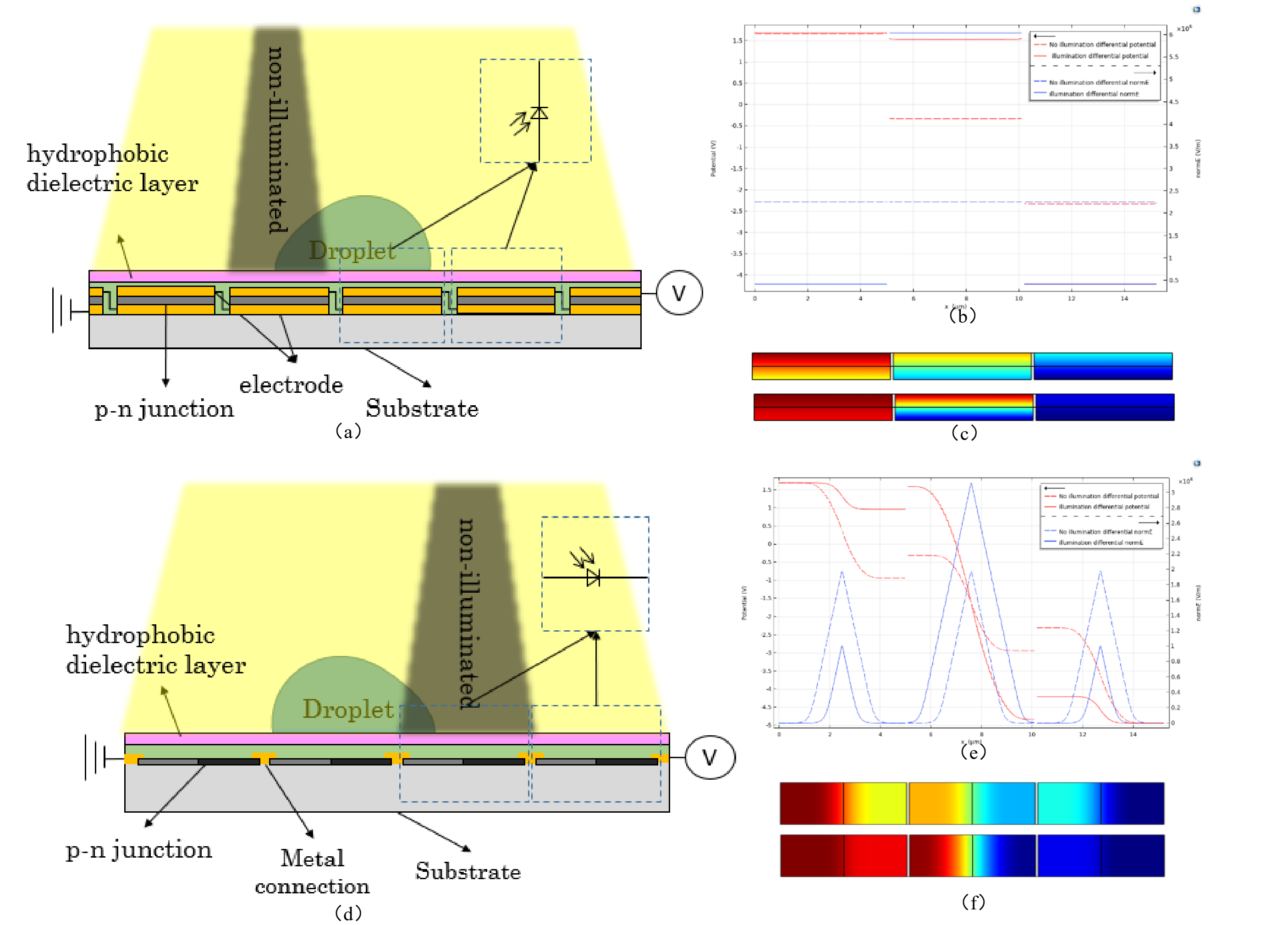

Fig.4.Device schematic and simulation results. (a) Schematic diagram of the OEW device placed horizontally at the pn junction. (b) Place the OEW device driving surface potential and the electric field mode one-dimensional line diagram horizontally before and after the illumination difference. (c) The lateral potential distribution of the OEW device placed horizontally with or without pn junction. (d) Schematic diagram of the OE junction device placed vertically. (e) Before and after the illumination difference, the pn junction is placed vertically on the driving surface potential of the OEW device and the one-dimensional line diagram of the electric field mode. (f) When there is no light, the pn junction is placed vertically on the driving surface potential of the OEW device

concentrated almost entirely at both ends of the pn junction, so that the pn junction working surface and the pn junction working surface adjacent to the low potential end generate a large potential difference. At this point, the droplet moves from the low side to the unlit area.

The second design is to place the pn junction vertically in the device, ie the side of the pn junction is used as the drive surface. According to Fig.4(d), the photodiodes are also connected in series in the circuit, and the illumination changes such that a large potential difference is generated between adjacent pn junctions, so that the droplets move from the low potential side to the unilluminated area. The difference is that the potential on the driving surface is continuously changed, and the potential difference is at most between two adjacent junction regions.

In summary, compared with the previous OEW device, the new device uses DC drive, which has little effect on the droplets and is convenient for portability improvement. At the same time, under the same applied voltage and the same illumination difference, the potential difference between the diodes is significantly greater than that of the photosensitive. The potential difference between the resistors, which will effectively increase the driving force of the DC drive. The pn junction is placed horizontally in the OEW device, and the potential between adjacent driving faces is hopping, which is similar to the way in which the array electrodes are sequentially energized in the conventional EWOD, and the driving force is relatively strong when the external voltage is the same. However, it can be seen from the structure diagram that the metal interconnection needs to be constructed during processing, the process is complicated, and the processing is difficult; the pn junction is placed vertically in the OEW device, and the change of the illumination condition also makes the potential difference of the adjacent pn junction driving surface become larger, but the potential It is continuously changing. When the external voltage is the same, the driving force is relatively weak. However, the processing technology of this structure is relatively simple and the processing difficulty is small. Considering all aspects of the factors, the second option can improve the driving force and make it easier to implement. It is a better choice.

V. CONCLUSION

In this paper, the current two main OEW microfluidic devices are studied and analysed. Compared with the EWOD microfluidic device, the OEW microfluidic device solves the EWOD by changing the potential difference of adjacent (virtual) electrodes by changing the illumination conditions. The problem of wiring difficulty in the microfluidic chip processing simplifies the peripheral control device and improves the stability of the device. However, the two devices are respectively driven by high-voltage high-frequency alternating current, which is not conducive to the portability improvement of the subsequent device and the problem that the DC drive is used but the driving force is relatively weak. Therefore, an OEW device based on diode structure is proposed in this paper. The basic principle is to drive the droplets by utilizing the characteristics of the diode switching in the DC circuit that changes with the change of the illumination conditions. The theoretical analysis of the voltage drop across the diode in series with the DC circuit varies with the illumination intensity. Finally, based on the analysis results, two diode-structured OEW devices are designed and simulated, and the two devices are compared and analysed the difference in the mechanism of driving droplets and the difficulty of processing.

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