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Photon Position Detector Consisting of Single-Electron Devices

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1. Introduction

A promising area of research on microphotonics is the development of solid-state sensors that can detect the position of incident single photons with high spatial resolution. This paper proposes one such device, a two-dimensional photon sensor consisting of single-electron circuits.

A single-electron tunneling junction can operate as a minute photon detector based on the photo-induced charging effect (see [1] and [2] for details). By arranging a lot of minute tunneling junctions into a matrix (each junction corresponding to each pixel), we will be able to make a two-dimensional position sensor with a high resolving power of 0.01-0.1 micrometers----a far higher resolution than that of existing position sensor devices, the microchannel plate photomultiplier.

The problem in developing such a position sensor is how to know the position of incident photons. It is difficult to lay row and column access lines through closely arranged tunneling junctions. Therefore, we developed a method of detecting positions based on the propagation of tunneling waves. The following sections describe the structure of our device and the method of position detection.

2. Device structure

The device we propose is shown in Fig. 1. It consists of a network of many single-electron oscillators----positively biased and negatively biased oscillators----regularly arrayed on a plane in a checkered pattern. Each oscillator is connected to its four neighboring oscillators by means of coupling capacitors. The bias voltage V_{dd} and $-V_{dd}$ are set to $|V_{dd}| < e/(2C_j)$ (e is the elementary charge and C_j is junction capacitance), so each oscillator operates monostably. The network is in a stable uniform state as it stands, and the node voltage of oscillators is V_{dd}. If a photon enters and excites an oscillator, electron tunneling due to photo-induced charges occurs in the oscillator, and an excitation of tunneling events, or a tunneling wave, propagates in all directions to reach the periphery of the network (see [3] for this wave propagation).

3. Propagation of tunneling waves in the device

Figure 2 shows a simulation of the wave propagation for a sample device consisting of 501 x 501 positively biased oscillators and 500 x 500 negatively biased oscillators. The node voltage of each positively biased oscillator is represented by a gray scale. On application of a photon to an oscillator in the network, a tunneling wave started at the point, expanded in all directions in the form of a circular wave, and reached the four corners (A, B, C, and D) of the device. The front line of the wave is uneven or irregular because the velocity of the traveling wave fluctuated in each direction throughout the process because of the stochastic waiting time of tunneling. The mean velocity depends on circuit parameters and was 100 divisions per 12.52 ns in this sample (for 'division', see Fig. 1). On the arrival of the wave, the positively biased oscillator at each corner produced tunneling and changed its node voltage from positive to negative. Waveforms of the node voltages are depicted in Fig. 3.

4. Determining the position of incident photons

Making use of the propagation of tunneling waves, we can determine the incident point of a photon as follows (see Fig. 4). Let us assume that a photon enters the device ABCD at a position P. Then a tunneling wave is generated at P and spreads out through the device at a velocity of v_0. As time passes, the wave front expands in all directions, as indicated by F_1-F_5, and reaches the periphery of the device. We observe the arrival of the wave at four diagonal points A, B, C, and D on the periphery and measure the time of wave arrival at each point. If the arrival time was t_0 at point A and $t_0 + t_1$ at point B, we can consider that position P is on the locus S_1 of points where the difference in the distance to two points A and B is $t_1 v_0$. That is, P is on hyperbola S_1 with loci A and B. Similarly, position P is also on hyperbola S_2 with loci B and C. Therefore, we can determine position P as the point of intersection of the two hyperbolas.

There are 6 possible sets of foci (AB, AC, AD, BC, BD, and CD), so we can draw 6 hyperbolas from the data of arrival time for the four diagonal points. All the hyperbolas intersect at one point if the wave velocity is constant, and therefore, two hyperbolas suffice to determine the position of P. In our device, however, wave velocity is not constant but fluctuates at every moment. Consequently, not all the hyperbolas intersect at one point, and there can be 15 intersection points in maximum (i.e., combination ${}_6\mathbf{C}_2 = 15$). Therefore we determined the position of P by calculating the mean coordinate of the 15 intersection points.

5. Calculation of the starting position of tunneling waves

Taking an example of Fig. 2, we calculated the starting position of the wave from the data of wave's arrival time given by Fig. 3, and compared the calculations with the actual position. (In calculation, we set the coordinates of the corner points A, B, C, and D to (0, 1), (1, 1), (1, 0), and (0,0). The actual starting point of the wave was (0.8, 0.7). Figure 5 is the result, showing 6 hyperbolas with their 15 intersection points. The mean coordinate of the intersection points was (0.799, 0.701) and approximately consistent with the actual starting position. This way, we can determine the starting position of tunneling waves in the device, and therefore, can know the position of incident photons.

References

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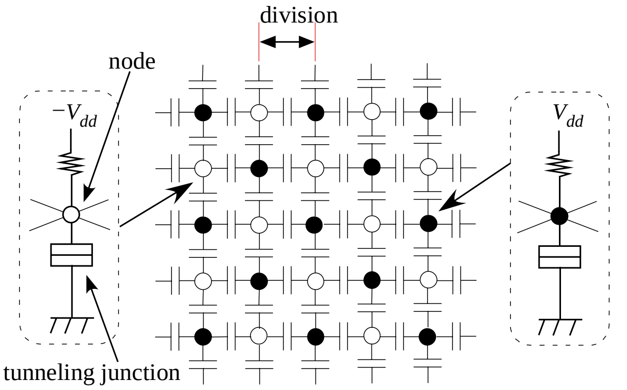

Fig. 1 Photon position sensor consisting of a network of single-electron oscillators. Closed circles and open circles are the nodes of positively and negatively biased oscillators respectively.

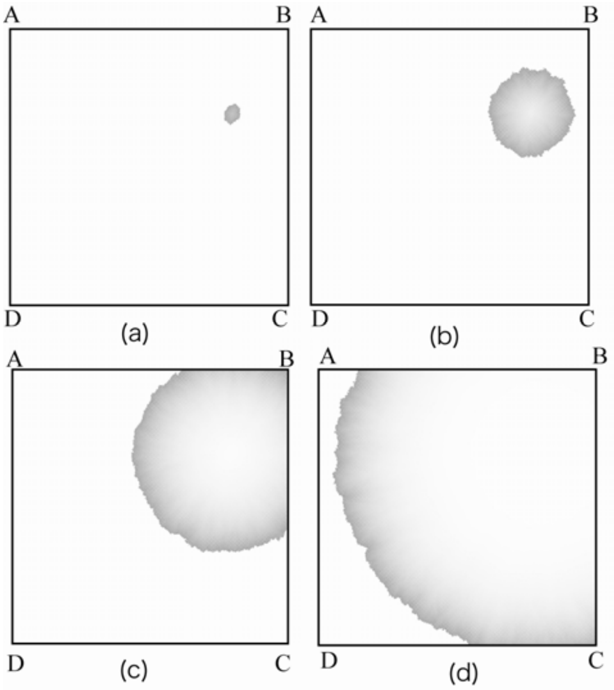

Fig. 2 Expanding tunneling wave in the device. Snapshots for four time steps, with time (t) after the occurence of the wave as t = 2ns for (a), t = 15 ns for (b), t = 50ns for (c), and t = 85ns for (d). The node voltage of each node is represented by a gray scale: light shading means high voltage, and dark means low voltage. Simulated with parameters: tunneling capacitance Cj = 10aF, coupling capacitance C = 2aF, tunneling junction conductance = 1μS, resistance R = 400MΩ, bias voltage Vdd = 4.8mV and -Vdd = -4.8mV, and zero temperature.

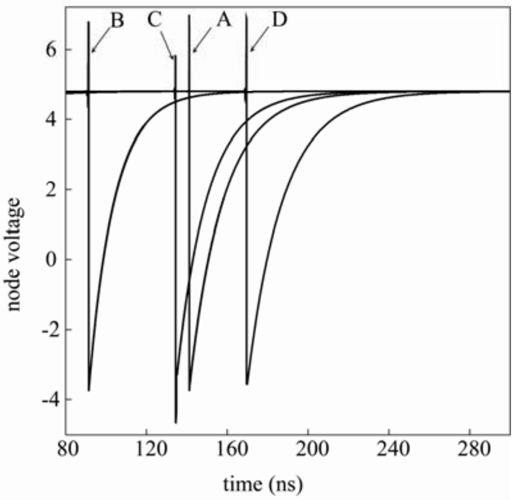

Fig. 3 Node voltage wave forms of the oscillators at corners A, B, C, and D of the device.

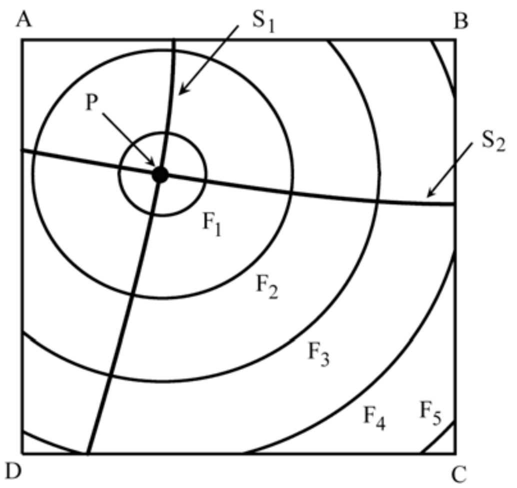

Fig. 4 Determination of the position of incident photons, making use of wave propagation. ABCD: device sorrounded by a square periphery. P: incident position of a photon, or the starting point of a tunneling wave. F1-F5: spreading wave front for four time steps. S1 and S2: two hyperbolas given by arrival-time data for points A,B, and C.

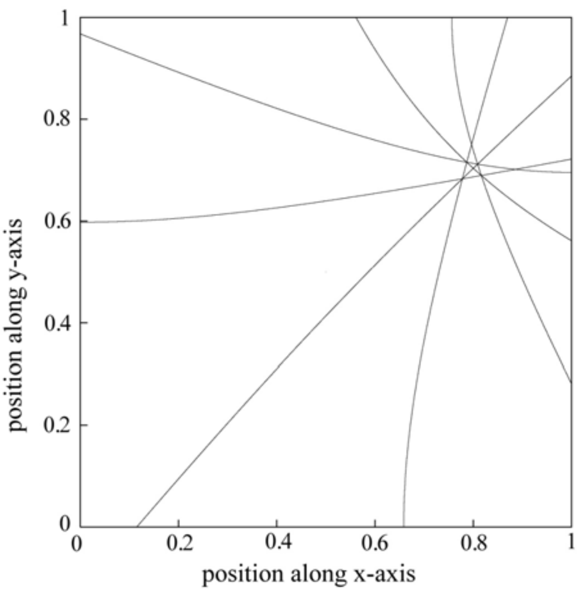

Fig. 5 Calculation of the starting position of tunneling waves. The six hyperbolas with their 15 intersection points are shown. The mean coordinate of the intersection points was (0.799,0.701) and approximately consistent with the actual starting position (0.8,0.7).