SENSOR MATRIX ARRAY FOR IMAGE PROCESSING IN VISUAL CORTEX

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ABSTRACT

A simple architecture of image processing has been developed to imitate the functions of the higher level visual cortex by using the new optoelectronic sensor. This sensor has the characteristics approximated by DOG (difference of Gaussian) functions. The characteristics are due to the negative photoinduced current (PIC) and the negative differential (ND) characteristics according to the forward bias voltage, which have been effectively obtained just for layer structures with a charge-storage layer of InAs/GaAs short period superlattice (SSL). By the simple matrix array using the sensor, the functions of selectivity to orientation angle, motion-direction and length of slit light in visual cortex have been imitated successfully.

1. INTRODUCTION

The massively parallel information processing is performed for the real-time recognition in the layer [1] and module [2] structure of the human visual cortex [3]. In the artificial neural network [4]-[6], the mathematical model composed of the MAC (multiply and accumulation) data processing and the nonlinear data processing is adopted to imitate the lower level functions of the visual cortex. In this field of research, a large problem of how to approximate the plasticity in synaptic contacts has been discussing. This problem becomes more serious as the number of synaptic contacts increases in order to realize the large-scale real-time data processing system which is more applicable to the industrial use. Although the various electric circuits [7], [8] have been developed to imitate the functions of the human visual cortex, the integration of the MAC processor is limited because of the increase of the number of the electric wiring. The introduction of optical methods to the circuits [9], [10], where the wireless processing is possible, would be expected to break the limitations of integration. In this case, however, it becomes difficult to perform the nonlinear signal processing like a sigmoid-function transformation, which is adopted usually in the artificial neural network model. The optical signals have to be eventually converted to the electric ones for the nonlinear processing. That is, in fact, the problem concerning the electric wiring still exists. Additionally, the determinant technology has not been developed to imitate the plasticity of synaptic contacts in either electronic or optoelectronic technique. Considering the overall situation as mentioned above, it is realistic to focus on the higher level functions of visual cortexes. In order to reduce the number of the electric wiring, the small scale integration of higher level functions is more effective than the large scale integration of lower level functions.

Recently, the functions of the higher level visual cortex become well-known in the fields of brain physiology [11], [12] and mathematical modeling. The distribution of optical sensitivity in visual receptive fields can be approximated by the DOG (Difference of Gaussian) function [13], [14], which is composed of two Gauss functions; one shows an excitatory postsynaptic potential element and the other shows an inhibitory postsynaptic potential element. They are formulated as exponential functions and the basis of the selectivity functions (e.g. orientation selectivity, motion-direction selectivity, length selectivity) to the slit light, which are some of the most well-known higher level functions of visual cortex. In order to realize the DOG function characteristics, new optoelectronic sensors with negative photoinduced current (PIC) must be developed, which means that the PIC decreases with the incidence of light (cf. inhibitory postsynaptic potential). On the other hand, the nonlinear properties realized by the confined quantum states of multi-quantum well (MQW) structures have attracted much attention for their possible application to unique devices [15]. Several studies have also been made to clarify the origin of the optoelectronic nonlinearity [16]. Stark localization in quantum wells performs the important roles in many cases. The transport of photogenerated electrons mainly contributes to the photocurrent. Contrary, the holes' contribution is negligible in many cases, because of the large effective mass which keeps them much more localized than the electrons [17]. However, influences of charge accumulation on the nonlinear characteristics have not been analysed in detail. In the previous work, the nonlinear relations between peak intensities and wavelengths at half maxima of photoluminescence spectra have been explained by the electric field distortion in the superlattice due to the accumulation of photogenerated holes.

In this paper, on the basis of the knowledge about the charge accumulation, we propose a new image processing architecture to imitate the higher level functions of a visual cortex.

2. STRUCTURE AND PRINCIPLE OF NEW SENSOR

2.1 Layer Structure
A cross-sectional diagram of stacked thin-film layer structure of new optoelectronic sensors developed in this work is shown in Fig. 1. The layer structure have been formed by molecular beam epitaxy on a Si-doped (001) GaAs substrate whose effective carrier density \( (N_d - N_a) \) is \( 1 \times 10^{18} \text{ cm}^{-3} \).

The following layers were successively grown: undoped GaAs/Ga\(_{0.7}\)Al\(_{0.3}\)As MQW structure (10 nm GaAs well and 40 nm Ga\(_{0.7}\)Al\(_{0.3}\)As barrier, 9 periods), GaAs (undoped, 12 nm) and GaAs top layer (undoped, 8 nm). The cap layer in Fig. 1 is composed of the GaAs subjacent layer, the storage layer and the GaAs top layer. The materials of storage layer are varied according to the sensors as shown in Table 1.

### 2.2 Principle of Sensor Device

In Fig. 2, a schematic energy band diagram near surface under a forward bias voltage is shown for a sample with a carrier-storage layer. A Schottky barrier lowering due to the forward bias voltage can cause an energy step between two regions in the cap layer, one is with an Al Schottky contact on the surface (contact region) and the other is with the bare surface surrounded by the Al metal of a ring-shaped contact (bare region). We have already observed nonlinear characteristics in the analysis of photoluminescence spectra from the bare region at 4.2 K and shown quantitatively it can be attributed to an electric field distortion induced by the accumulation of photogenerated holes in the bare region. In the previous work, the holes’ accumulation was realized at 0 V and can be explained by considering a Schottky barrier lowering due to an image force at 4.2 K. In this work, we have designed the device structure to accumulate the charge at 300 K, which is realized by a Schottky barrier lowering induced by the forward bias voltage. When optical signals are incident on the surface of the bare region in Fig. 1, holes and electrons photogenerated in the cap layer can be accumulated in the storage layer of the bare region and contact region, respectively. The accumulated electrons in the storage layer of the contact region increase the barrier height for the electrons drifted to Schottky contacts. The mechanism is shown schematically in Fig. 3. The accumulated electrons (solid circles) in the storage layer of the contact region increase the energy level near interface between the cap layer

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<table>
<thead>
<tr>
<th>Sensor Number</th>
<th>Material of Storage Layer</th>
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<tbody>
<tr>
<td>1</td>
<td>(InAs)(GaAs) SSL</td>
</tr>
<tr>
<td>2</td>
<td>(InAs)(GaAs) SSL</td>
</tr>
<tr>
<td>3</td>
<td>In(<em>{0.3})Ga(</em>{0.7})As alloy</td>
</tr>
<tr>
<td>4</td>
<td>InAs</td>
</tr>
<tr>
<td>5</td>
<td>GaAs (i.e. no storage layer)</td>
</tr>
</tbody>
</table>

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and Al electrode (the energy levels before and after the accumulation are shown as a broken line and a solid line, respectively). This means the increase of the effective barrier height for the electrons drifted from AuGe ohmic electrode to the Al electrode. That is, the forward bias current decreases due to the accumulation of photogenerated electrons (negative PIC). In addition, the number of accumulated electrons increases with the forward bias voltage, because the energy step between the contact and bare regions is enhanced. This means that the difference between the energy levels before and after the accumulation in Fig. 3 increases. Therefore, the absolute values of negative PIC increase with the forward bias voltage (ND characteristics). At higher forward bias voltages, the accumulated electrons decrease by the Fowler-Nordheim tunneling or carrier overflow and the PIC increases abruptly to the ordinary (positive) value. It will be expected that the ND characteristics are enhanced by confining the photogenerated electrons more strictly.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Photoinduced Currents

The dependence of PIC on forward bias voltage is shown in Fig. 4 for sensor 1. Negative values of PIC are obtained above 1.1 V, although the total current values are positive. In addition, the absolute value of the negative PIC increases as the forward bias voltage increases from 1.1 V to 2.5 V (ND characteristics). The maximum absolute values of negative PIC are 49 µA and 58 µA under the incident laser power of 14.5 mW/cm² and 30.5 mW/cm², respectively. The ND characteristics in Fig. 4 can be described approximately by the DOG function. The general description of DOG function G(x) is:

\[ G(x) = A \exp\left[\frac{-(x-a)^2}{\sigma_e^2}\right] - Q \exp\left[\frac{-(x-a)^2}{\sigma_i^2}\right], \]

where A, Q and \( \sigma_e \), \( \sigma_i \) are peak values and standard deviations of two Gauss functions, respectively, and a is the peak position of G(x). The experimental curve in Fig. 4 has been approximated successfully by the DOG function (1) under considering G(x) as the photoinduced current and x as the forward bias voltage (broken curve in Fig. 4). In this case, the parameters in (1) are as follows: \( A=100 \), \( Q=65 \), \( \sigma_e=0.28 \), \( \sigma_i=1.02 \), \( a=3.2 \). The maximum absolute values of negative PIC are compared in Fig. 5 for the sensors shown in Table I. The largest value in Fig. 5 is 149 µA, which has been obtained for sensor 2 under 15.0 mW/cm². The ND characteristics can be obtained in the case of sensor 3 and 4 though it is not obtained in the case of sensor 5. It should be noticed that the ND characteristics in the case of the storage layer of InAs/GaAs SSL (sensor 1, 2) are extremely outstanding compared with those in the case of the storage layer of In\(_{0.7}Ga_{0.3}\)As alloy or InAs (sensor 3, 4).

3.2 Time Dependence of Forward Current

The effect of InAs/GaAs SSL storage layer can be con-
firmed by another evaluation. In Fig. 6, the dependence of forward current (FC) on the time after voltage application is shown. The FC of sensor 1 decreases with the time although that of sensor 3 or sensor 4 is almost constant. The gradual decrease of FC means the gradual accumulation of photo-generated electrons in the Schottky contact region of the InAs/GaAs SSL storage layer. In the case of the storage layer of In$_{0.3}$Ga$_{0.7}$As alloy (sensor 3) or InAs (sensor 4), most of photogenerated electrons disappear due to defect-induced energy levels before accumulated in the contact region.

3.3 Ratio of PIC to Forward Current

As mentioned in Fig. 4, one of the outstanding features of this sensor is the negative value of PIC in spite of the positive value of forward current. It has been confirmed experimentally the ratio of the absolute PIC value to the forward current is 0.40 in the case of 30.5 mW/cm$^2$ of incident laser power and 2.5 V of forward bias voltage in Fig. 4. On the other hand, the maximum ratio value of sensor 3 is 0.07 in the case of 29.0 mW/cm$^2$ of incident laser power and 1.6 V of forward bias voltage. The large ratio values as well as the large absolute values of negative PIC are obtained in the case of the storage layer of InAs/GaAs SSL.

4. APPLICATION TO ARTIFICIAL VISUAL CORTEX

An matrix array using sensor 1 or 2 has been designed to imitate the higher level function of human visual cortex as shown in Fig. 7. The characteristic curves shown in Fig. 4 are approximated by DOG functions, which also approximate the sensitivity distributions in the receptive field of human visual cortex [18]. The selectivity (orientation selectivity, motion-direction selectivity and length selectivity to slit light) due to the DOG functions has been observed in a human simple cell, complex cell and hypercomplex cell, respectively [18]. In Fig. 7, the sensors 1 (or 2) are connected in line without (lines 1, 2, 11 and 12) or with (lines 3-10) an electric resistance $C$. Each line is connected to a bus line via an electric resistance $A$ (lines 1, 2, 11 and 12) or via an electric resistance $B$ (lines 3-10). The resistance of $A$ is larger than that of $B$. Under these conditions, the voltages applied to the sensors in the lines 3-10 decrease and the PIC of the sensor can be changed from the positive value to the negative one as the sensor comes apart from the bus line. On the other hand, the PICs of the sensors in the lines 1, 2, 11 and 12 are identical and can be set to the negative values. The total PIC of the optoelectronic sensing circuit shown in Fig. 7 has been estimated and the results are shown in Fig. 8. The number of sensors is $L_m \times W_m$ and each...
sensor is not shown to avoid the complication. Each line of sensor array in Fig. 7 is represented by broken-line rectangle in Fig. 8 (a). The size of slit light (a hatched rectangle) is L×W and the angle between the slit light and the bus line (X axis) is represented by θ. The dependence of the total PIC on the angle θ is shown in Fig. 8 (b). The total PIC is positive only in the case of θ = 0. This means the orientation selectivity if the threshold value of PIC is set to 0. The relations between the total PIC, Y value and length of slit light are shown in Fig. 8 (c). The total PIC is positive only in the case of Y = 1 and L < 9. This means that the total PIC is positive only when the motion-direction of the slit light is coincident to the direction of Y axis (motion-direction selectivity) and the length of the slit light is equal or less than 8 (length selectivity).

5. CONCLUSIONS

A simple architecture of image processing has been proposed by using the new optoelectronic sensor with the negative PIC and the ND characteristics.

The maximum absolute value of the negative PIC is about 150µA. The ratio value of the absolute PIC to the forward current is 0.40 at the temperature of 300 K. The large ratio values are obtained for the sensor with the storage layer of InAs/GaAs SSL. The excellent crystal quality of the InAs/GaAs SSL is extremely effective. The negative PIC and the ND characteristics have been approximated by the DOG function and it means the new sensor makes it simple to design a matrix array imitating the higher-level image processing functions in visual cortex. As a result, the selectivity functions of visual cortex, which are due to the DOG-functionlike distribution of optical sensitivity in visual receptive fields, have been confirmed by simulation experiments using the real characteristics of the sensor. One of advantages of using the new sensor is that the number of electronic parts to obtain the DOG-functionlike characteristics can be diminished. For example, we have estimated that 61 electronic parts are needed to obtain the characteristics by using the ordinary devices. The advantage will be enhanced by developing a Si sensor including the storage layer of Si/SiGe superlattice based on the same principle.

REFERENCES