Two-Dimensional Near Infrared Sensor with Low Noise and Wide Wavelength Range

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A two-dimensional near infrared image sensor with the cut-off wavelength of 2.35 µm has been successfully developed by using InGaAs/GaAsSb type-II quantum well structures as its absorption layer. The 250-pair InGaAs (5nm)/GaAsSb (5nm) quantum well structures lattice-matched to InP substrates were grown by metal organic vapor phase epitaxy. The p-n junctions were formed in the absorption layer of each pixel by the selective diffusion of zinc. The sensor chip with 320 × 256 pixels at 30 µm pitch, in which each pixel has an 18 µm × 18 µm light receiving area, was hybridized to a read-out IC with indium bumps. More than 99% pixels operated properly. A Peltier cooler was used as the cooling system, enabling the downsizing of sensing systems. The dark current of each pixel was 3 pA at -60°C, which is lower than that of the conventional sensor at the same temperature. The responsivity showed good linearity with respect to the input power. Therefore, this sensor is expected to be used for the detection of weak optical signals and the quantitative, real-time image analyses of various materials in the food and phermaceutical industries.

Keywords: near infrared, sensor, type-II quantum well, low noise, imaging

1. Introduction

Many molecules have overtones and combination tones of fundamental vibrations in the near infrared region between 1.0 µm and 2.5 µm. As the absorptions of these tones are weaker than that of fundamental vibrations in the mid infrared region over 3 µm, the near infrared light arrives at the inside of matarials and therefore is expected for the non-destractive analyses. Recently, the near infrared spectroscopy has been attracting notice from the view point of the safety and the quality control in many production field such as pharmaceutial and food industries, or from the view point of diagnoses in lifescience fields. Sumitomo Electric Industries, Ltd. has produced the near infrared diagnostic equipment "Compovision" which makes it possible to image the distribution of composition and concentration of materials in real time non-destructively, which is difficult by the conventional imaging inspection method.

In the near infrared region, the identification of material is generally difficult because the absorptions of many materials overlap and the forms of spectra are complicated. However, this problem has been solved by the statistical data processing technology such as chemometrics. On the other hand, five items as follows are needed for the near infrared sensor: (1) High responsivity and low noise for detecting weak absorption such as overtones and combination tones; (2) Operation not with a large-scale cooling system such as liquid nitrogen but with a small cooling system such as Peltier device; (3) High speed operation for real-time inspection; (4) Good linearity of responsivity with respect to the strength of light for quantative analyses; and (5) Array sensor for imaging (in particular, a two-dimentional array sensor is preferable to do both spectral measurement and spatial position measurement at the same time). In this paper, a two-dimentional near infrared sensor which is a key device for the compositional imaging system "Compovision" will be introduced.

2. Near Infrared Sensor with Type-II Quantum Well Structure

The near infrared sensors are classified into two types. One is the photoconductive type such as PbS and PbSe, and the other is the photovoltaic type such as Ge, InAs, InSb, HgCdTe and InGaAs. In general, the photovoltaic type is superior to the photoconductive one from the view point of response time and linearity of responsivity to the strength of incident light. Among the photovoltaic type, Ge, InAs, InSb and HgCdTe sensors have high dark currents and need large-scale cooling systems such as one using liquid nitrogen. On the other hand, the InGaAs sensor lattice matched to InP substrate shows low dark current and high responsivity. Also, mass production technology of the InGaAs sensor has progressed because it is used for the photodiode of optical fiber communications, and the two-dimensional array sensor is already on the market. However, because of its cut-off wavelength of 1.7 µm, the sensor can only analyze restricted materials. The cut-off wavelength can be made longer up to about 2.6 µm by increasing the indium composition of InGaAs. But the dark current due to crystal defects becomes large because of lattice-mismatch to InP. In addition, it is difficult to fabricate two-dimensional array sensors with large chip size because of the difficulty of homogeneous epitaxial growth. Currently, the sensor which has a two-dimensional array and can operate in the near infrared region up to 2.5 µm is made of HgCdTe. However, it is difficult to apply this sensor to the wide-use analytical equipment because not only it is very expensive due to its large-sale cooling system but also its constituent elements have big impact against the environment.

Recently, type-II quantum well structures attract attention as materials to realize both longer cut-off wavelength and lower dark current, which is difficult for the semiconductor bulk materials. The InGaAs/GaAsSb type II quantum well structure is a candidate for 2 μm-range infrared sensor material(1),(2). As shown in **Fig. 1**, the absorption which occurs at the overlapped part between the wave-function of electrons in the conduction band of InGaAs and the wave-function of holes in the valence band of GaAsSb corresponds to the wavelength of 2 μm range. In this material system, both InGaAs and GaAsSb are lattice-matched to InP substrate and the crystal defects due to lattice mismatch is not generated and therefore low dark current is expected. Also, because the effective small bandgap is realized by combining large bandgap materials, noise current due to thermal excitation or Auger recombination is expected to be suppressed. Moreover, the cut-off wavelength can be easily adjusted by changing the layer thickness of quantum wells.

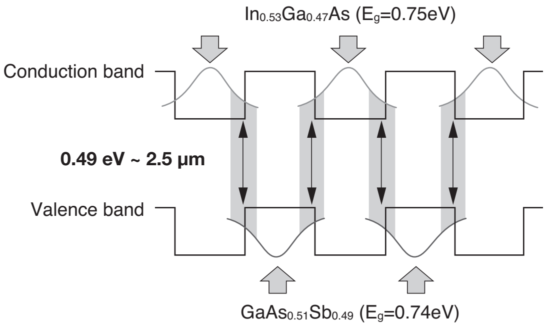

Fig. 1. Band structure of InGaAs/GaAsSb type-II quantum wells (layer thickness is 5nm/5nm)

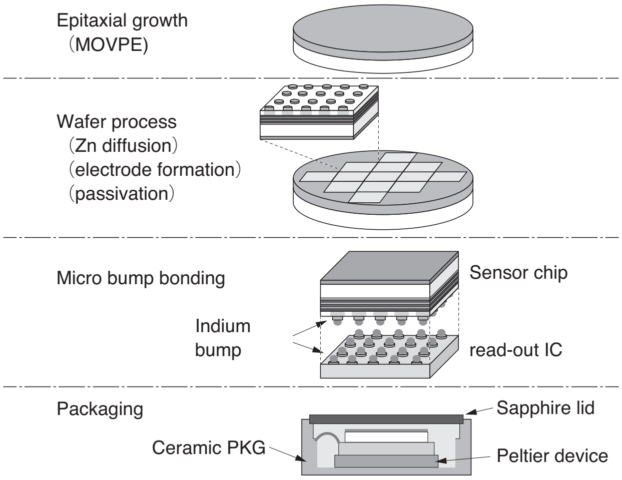

Fig. 2. Fabrication flow of sensor

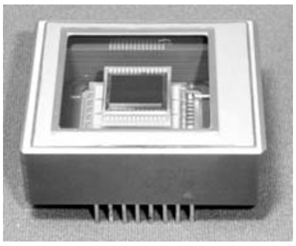

Photo 1. Two-dimensional array sensor

3. Fabrication of Two-Dimensional Array Sensor

A two-dimensional array sensor with 320 × 256 pixels was fabricated. Each pixel has an 18 μm × 18 μm light receiving area and is arranged by 30 μm pitch. The fabrication process is illustrated in **Fig. 2**.

An InGaAs buffer layer, an InGaAs/GaAsSb quantum well absorption layer (layer thickness: 5nm/5nm, pair number: 250), an InGaAs layer and an InP cap layer were grown on a S-doped (100) InP substrate by metal organic vapor phase epitaxy (MOVPE).

The p-n junctions were formed in the absorption layer by the selective thermal diffusion of zinc in the 18 μm × 18 μm region arranged by 30 μm-pitch using SiN mask. The p-electrodes made of Au-Zn were formed on the InP cap layer of each pixel and the n-electrode made of Au-Ge-Ni were formed on the rear surface of the InP substrate as a common electrode. As this sensor is the rear-illumination type, SiON as an anti-reflection film was deposited on the rear surface of the InP substrate.

The sensor chip was bonded to a complementary metal oxide semiconductor (CMOS) read-out integrated circuit (read-out IC) by indium bumps. After that, the hybridized chip was assembled in a ceramic package with a Peltier device as shown in **Photo 1**. The sapphire lid with anti-reflection film was used for a window. The photo-current generated in each pixel of the sensor chip was output as voltage signals through the capacitive transimpedance amplifier (CTIA) of the read-out IC. The signals were changed to digital signals by the field-programmable gate array (FPGA).

4. Characteristics of the Sensor

A portrait obtained by the developed two-dimensional array sensor is shown in **Photo 2**. It was photographed under the illumination of a conventional halogen lamp with the frame rate of 100 Hz and the integration time of 1 msec. The signal was output by 14 bit. The clear gradation that reflects the quantity of moisture was obtained at the skin and hair. The pixels with defect were less than 1% in the sensor.

4-1 Dark current

The temperature dependence of dark current at V_R=60 mV of a senor with an 18 μm × 18 μm light receiving area is shown in **Fig. 3**. The dark current (I_d) at the temperature (T) is generally described by the following equation:

$I_d \propto \exp(-E_g/nkT)$,

where E_g is a bandgap energy of the absorption layer, k is Boltzmann constant, and n is a constant. The dark current at the lower bias voltage consists of diffusion current gen-

Photo 2. Portrait photographed by the developed two-dimensional sensor

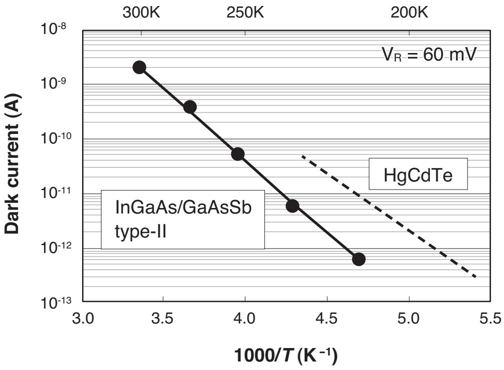

Fig. 3. Temperature dependence of dark currents of InGaAs/GaAsSb type-II quantum well sensor and HgCdTe sensor

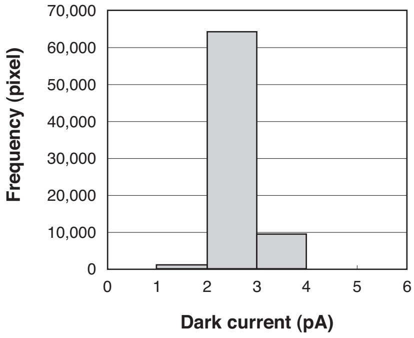

Fig. 4. Histogram of dark currents in 320×256 pixels. Measured at V_R=1.2V and T=213K

erated near the depletion region and generation-recombination current generated via traps in the depletion region. The n-value is unity when the diffusion current is dominant, and becomes two when the generation-recombination current is dominant. Considering E_g=0.49eV in the case of the developed sensor, the n-value is calculated to be 0.92 from the slope on the graph of **Fig. 3**, which shows the diffusion current is dominant. The dark currents of the HgCdTe sensor were compared at the same light receiving area and bias voltage$^{(3)}$. In **Fig. 3**, dark currents of the HgCdTe sensor are also shown as the dotted line. Our developed sensor has lower dark current than the HgCdTe sensor by one order when compared at the same temperature. This shows that the InGaAs/GaAsSb type-II quantum well structure is promising as the sensor material with low noise. The histogram of dark currents in 320 × 256 pixels at -60°C is shown in **Fig. 4**. The dark current of each pixel is between 2 pA and 4 pA. This result shows the dark currents are homogeneous.

4-2 Responsivity

The responsivity characteristics in the wavelength region over 2 µm were measured using a spectrophotometer. As shown in **Fig. 5**, the sensor can detect the light up to 2.35 µm, which corresponds to the effective bandgap energy of the type-II quantum well structure.

Furthermore, responsivities at the wavelength of 1.29 µm, 1.53 µm, 1.96 µm and 2.20 µm were measured using band pass filters. As shown in **Fig. 6**, the linearity of responsivity with respect to the strength of incident light was good for every wavelength. Almost all of the operable pixels (>99%) showed the same responsivity characteristics.

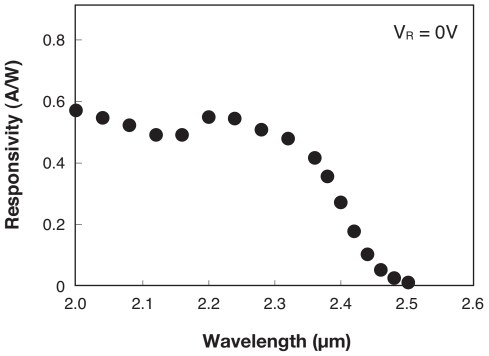

Fig. 5. Spectral responsivity

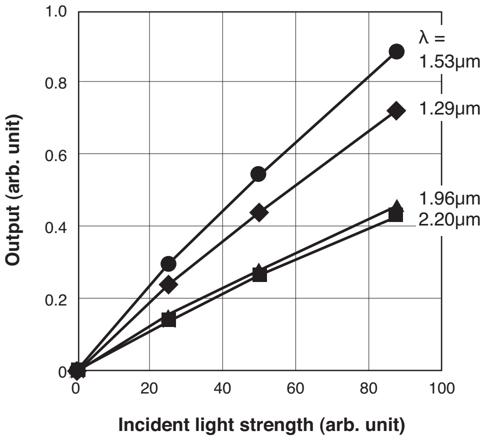

Fig. 6. Linearity of responsivities

These results show that our sensor is suitable for analyzing the distribution of composition and concentration of materials by imaging.

5. Conclusion

With growing expectations for the non-destructive and non-invasive analyzing equipment using near infrared spectroscopy, the two-dimensional infrared sensor that can detect light in the near infrared region up to the 2 μm band has become more important. In this development, the InGaAs/GaAsSb type-II quantum well structure was adopted to obtain longer cut-off wavelength and lower dark current, both of which are difficult to obtain with semiconductor bulk materials. As a result, a two-dimensional array sensor with 320 × 256 pixels was realized. This sensor can detect light in the near infrared region up to 2.35 μm and is operated with a Peltier cooling device. Furthermore, this sensor has a good linearity of responsivity and high frame rate of 100 Hz.

Photo 3 compares sample images of the mixture of sugar and salt photographed by the developed two-dimensional array sensor and a charge coupled device (CCD) camera. Although sugar cannot be distinguished from salt in the visible image photographed by a CCD camera, it can be distinguished in the near infrared image as sugar is dark-colored. The developed sensor can be used not only for material distinction but also for quantitative analysis because of its good linearity of responsivity.

The production costs of this sensor will be reduced by using MOVPE technology, which is suitable for the mass production of epitaxial wafers, and mass production techniques that have been cultivated through the development of photodiodes for optical fiber communication. With the above described features, this sensor is expected to be used in new fields as an efficient general-purpose 2 μm-range infrared sensor.

(a) Visible image (b) Near infrared image

Photo 3. Comparison of visible image and near infrared image of sugar-salt mixture.
As both materials are white, they cannot be distinguished from each other in (a). In (b), however, they can be distinguished as sugar absorbs near infrared light and appears dark.

· Compovision is a trademark or registerd trademark of Sumitomo Electric Industries, Ltd.

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