1. Introduction

Advances of LSI technology indicate the inadequacy of electronic systems in signal propagation and needs for optical interconnection. As electronic devices are mainly made of Si, fabricating photonic devices on Si is an effective method for optoelectronic system integration [1]. The Al/SiO$_2$/Si tunneling structure has been reported as one of photodetectors fabricated through MOS compatible processes [2]. However, the optical-power density dependence of photodetective characteristics has not been examined.

In this study, we have examined photodetective characteristics of the MOS tunneling diode with Al grid gate as a function of optical-power density, and observed the SiO$_2$ film thickness dependence of steep change in on-off ratio. We have also proposed a model of the mechanism.

2. Experiment

The wafer was n-type Si(100) with a resistivity of 10-20 $\Omega$·cm. The wafers were chemically cleaned and thermally oxidized at 1000°C in oxygen gas of an atmospheric pressure. The thickness of an SiO$_2$ film was measured by ellipsometry. The Al electrode was formed on the SiO$_2$ film by evaporation and patterned to be grid gate by photolithography. The electrode area was 1.62×10$^{-3}$ cm$^2$.

Electrical characteristics of MOS tunnel diodes were measured under light irradiation. The light source was He-Ne laser (wavelength: 632.8nm). The energy of the laser is larger than the band gap of Si so that the electron is excited from valence band to conduction band. The optical power density $P_{in}$ was controlled with dark filters.

3. Results and discussion

Fig. 1 shows the variation of current density - gate voltage (J-V$_g$) characteristics as a function of incident light power density for a 2.6nm-thick SiO$_2$ MOS tunnel diode. Fig. 2 shows the relationship between the on-off ratio and $P_{in}$ at $V_g = -2$V. The on-off ratio was calculated from the ratio of the photo current density $J_{photo}$ and the dark current density $J_{dark}$ as $10\log_{10}\left(J_{photo}/J_{dark}\right)$. While the on-off ratio is almost zero under low power density, it steeply increases at a certain power density. It is defined as threshold optical-power density $P_{th}$. In Fig. 2, $P_{th}$ shifts as a function of oxide thickness. $P_{th}$ sensitively increases as the thickness of SiO$_2$ film decreases.

To discuss the mechanism of photodetection, the depletion width $w$ in Si was calculated from 1MHz capacitance – gate voltage (C-V$_g$) characteristics. Fig. 3 shows the depletion width as a function of $P_{in}$ when the gate voltage of -2V was applied. $w$ begins to shorten at around $P_{th}$. Under dark or low optical power density, $w$ is wide and the deep depletion is occurred. The oxide voltage is low as shown in Fig. 4, and electrons hardly tunnel from Al to Si. $w$ is shortened under high power density. It induces the increase of oxide voltage and tunneling current. It is considered that $w$ is shortened and inversion layer is formed by optically generated carriers when strong light is irradiated and optical generation is dominated rather than thermal generation [3].

Fig. 5 shows the optical-generation rate of minority carriers (holes). The dashed lines denote thermally generated rate of minority carriers in depletion layer under dark condition. The rate is obtained from the lifetime which is calculated from capacitance – time (C-t) characteristics by Zerbst method [4]. The optical-power densities of intersections of dashed lines with a solid line define threshold densities, at which the optical generation is occurred at the same rate of thermal generation. While $P_{th}$ is higher than the threshold, the optical generation is dominant rather than the thermal generation and $w$ is shortened and the inversion layer is formed. When the SiO$_2$ film is thin, many electrons are injected to Si by tunneling and holes near the Si/SiO$_2$ interface are recombined with tunneling electrons, and hole density decreases. Therefore, higher light power is required to shorten the depletion layer for a thinner SiO$_2$ film.

Fig. 6 shows the comparison between $P_{th}$ obtained from the on-off ratio and from the generation rate. $P_{th}$ from generation agrees well with that from the on-off ratio. Therefore, the steep change of the on-off ratio is explained by the balance of generation processes.

4. Summaries

We have elucidated photodetective characteristics of the MOS tunneling diode. The steep change of on-off ratio is occurred when the optical generation becomes more dominant than the thermal generation. The shift of threshold optical-power density is explained by the difference of the number of tunneling electrons through the SiO$_2$ film. The MOS tunneling structure is expected as digital photodetectors with threshold optical-power density controlled by the SiO$_2$ film thickness.
References

Fig. 1 Current density – gate voltage characteristics of MOS tunneling structure with 2.6 nm-thick SiO₂ film under light irradiation.

Fig. 2 On-off ratio as a function of optical-power density for different SiO₂ thicknesses at gate voltage of -2 V.

Fig. 3 Depletion width as a function of optical-power density for different SiO₂ thicknesses at gate voltage of -2 V.

Fig. 4 Energy band diagram of Al/SiO₂/n-Si tunneling structure at negative applied voltage for high optical-power density.

Fig. 5 Calculated generation rate versus optical-power density. Dashed lines denote thermal generation rate under dark condition.

Fig. 6 Threshold optical-power density from on-off ratio characteristic and from carrier generation shown in Fig.5 as a function of SiO₂ thickness.