Abstract

There are abundant emission lines and band radiations from various atomic gases, molecular gases, and solid substances in the infrared region. We can diagnose the physical and chemical states of interstellar space and protoplanetary disks through the features of their emission lines and band radiation. The ultimate goal of this research is to realize a high-sensitivity, large-format infrared detector capable of spectroscopic observations in the mid-to-far infrared wavelength range (30－200 μm), including the unexplored wavelength band of 30－60 μm, with a Noise-Equivalent Power of $<10^{-19}$ W/$\sqrt{\text{Hz}}$. Therefore, we must develop an integrated detector that combines a Ge-based photodetection layer with a Si-based cryogenic readout integrated circuit (CROIC). The CROIC employs an already developed 32 × 32-pixel CTIA circuit fabricated using fully depleted silicon-on-insulator (FD-SOI) CMOS technology. A significant issue arises from electrical connection failures due to mismatches in thermal expansion coefficients between Ge and Si during cooling. To address this issue, we adopt a Si/Ge heterojunction for the photodetection layer. However, there are still no examples of detectors fabricated on the Ge layer side of Si/Ge heterojunctions. Furthermore, for the detector composed of the Ge layer, we use a two-dimensional BIB-type Ge detector, which previous studies have demonstrated to exhibit optical sensitivity in the 30-200 μm wavelength range. Therefore, as a fundamental development of a mid- to far-infrared detector, we must fabricate a two-dimensional BIB-type Ge detector on a Si/Ge heterojunction and evaluate its operation and optical response.

We designed three types of devices based on Si/Ge heterojunctions. For Type A, we adopted a square spiral electrode structure measuring 580 × 580 μm, similar to previous studies that used only a Ge layer. The width of the active layer was set to 10 μm, block layer width to 4 μm, and the electrode width to 4 μm. The Type A design raised concerns about breakdown phenomena arising from localized electric-field concentration near the spiral corners. To mitigate this issue, we designed Type B devices with rounded corners on the square spiral to reduce local electric-field concentration. Furthermore, to achieve higher optical sensitivity than that reported in previous studies, we designed Type C devices by rounding the spiral corners while it is improved the filling factor (the ratio of the optical absorption layer area to the total device area), thereby effectively increasing the optical absorption length through reduced reflectance. For the Type C devices, the widths of the active layer, block layer, and electrodes were all set to 4 μm. The three devices (Type A, B, and C) were cooled to the temperature of 2.4 K and simultaneously illuminated with blackbody radiation. Their operation as optical sensors was verified, and the Current-Voltage characteristics and wavelength-dependent responsivity were measured for all devices under identical conditions.

As a result of the measurements, all devices are confirmed to respond to infrared radiation, as evidenced by the opening and closing of the blackbody radiation shutter. The current-voltage characteristics exhibit asymmetry with respect to the effective detector bias voltage, and differences in overall characteristics are observed among the three device types. The current-voltage characteristic of Type A is similar in shape to that reported in previous studies. At an effective detector bias voltage of −35 mV, the responsivity of Type A is 2 times higher than that of the previously reported device. At the same time, that of Type B is 5 times higher than that of the previously reported device. Moreover, the responsivity of Type C is 11 times higher than that previously reported. The spectral response

curves of all devices exhibit local peaks at wavelengths of ∼130 μm, ∼150 μm, and ∼180 μm. These peaks differ from those reported previously at ∼110 μm and ∼155 μm. In addition, local peaks at ∼40 μm for Types A and B and at ∼30 μm for Type C are observed for the first time in this study.

Type A is based on the same electrode structure as that used in the prior study, yet exhibits an absolute sensitivity 2 times higher than conventional type. This is attributed to the cooling of the Si/Ge heterojunction, which induces tensile stress of approximately 100 MPa in the Ge layer. This stress increases carrier mobility in the neutral-impurity-scattering region, thereby enhancing responsivity. We attribute the 2 times increase in the absolute responsivity of Type C compared with that of Type B not only to differences in the filling factor and quantum efficiency, but also to an electric-field enhancement effect at the electrode edges. This enhancement increases the number of electric field lines penetrating the depletion layer, thereby increasing the apparent photon flux. Furthermore, the bias dependence of absolute responsivity can be explained by the difference in isotropic etching amounts among different types and the influence of the electric field enhancement effect. Regarding the spectral response curves, we explain the observed local peaks at approximately ∼130 μm, ∼150 μm, and 180 μm by the splitting of the valence-band maximum and impurity levels induced by tensile strain in Ge. In addition, we attribute the local peaks at approximately ∼40 μm and ∼30 μm to surface plasmon resonances excited by coupling between charge-density waves of free electrons at the interface between dielectric Ge and Au electrodes and surface electromagnetic waves. The fundamental difference lies in the fact that conventional devices irradiate infrared light from the electrode formation surface, whereas this device allows infrared light to pass through the germanium, resulting in a different wavelength. As part of the elemental development for mid-to-far infrared detectors, a two-dimensional BIB-type Ge detector was formed on the Ge layer side of a Si/Ge heterojunction.