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Infrared detection with silicon nano transistors

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1. Introduction

Infrared (IR) sensor is useful for various applications such as image sensing and material analysis. Si-based IR sensors could have fascinating features, e.g., miniaturization and embedization into LSIs. However, Si has little or no IR absorption characteristics due to its indirect band-gap energy of 1.1 eV, which keeps Si away from major IR sensors.

In this paper, we report IR sensing using nano-scale Si MOSFETs. An IR signal excites conduction-band majority electrons and some of them are injected into a memory node (MN) electrically formed by a MOSFET. Small signal originating from electrons stored in the MN are detected by an electrometer with single-electron resolution. Additionally, the MOSFET controls the number and energy of electron for injection to the MN. This leads to the electrical control of the sensitivity, suggesting the possibility of highly functional IR sensors.

2. Device structure and principle

The fabricated device is shown schematically in Figs. 1(a) and (b). This is in effect a gain cell (GC), which we have used for charge sensing with single-electron resolution [1]. The fabrication process is the same as that in a previous paper [2], but the present GC has a wide-area region for IR absorption close to the MN.

The upper gate (UG) induces the inversion layer that serves as the source [or electron reservoir (ER)]/drain (or MN) of the MOSFET (MTr). When the lower gate (LG) turns the MTr off, the MN is electrically formed at the tip of the wire channel [Fig. 2 (a)]. When IR signal, whose wavelength is λ μm, is radiated, electrons in the ER are excited by E_{ex}=1.24/λ eV and some of them are emitted to the MN [Fig. 2(b)]. Since the time interval or frequency of the electron emission to the MN, which corresponds to the IR signal to be detected, depends on E_{ex} and the potential barrier controlled by the LG [2], the GC has E_{ex}(or λ)-dependent sensitivity. Additionally, since the density of excited electrons is proportional to that of electrons in the ER, IR-signal sensitivity can be also controlled by using the UG. The electrons in the MN, i.e. IR signal, are read out as the change in current I_D flowing through the MOSFET (ETr), which is capacitively coupled to the MN.

3. Experimental results

Measurement temperature was 300 K. We first show the characteristics of the ETr current I_D (Fig. 3) and the sensing of stored electrons (Fig.4) without IR irradiation. As shown in Fig. 3, when the MTr opened and the ER voltage V_{ER} was changed, I_D-V_{UG} characteristics were shifted because of the capacitive coupling between the MN and ETr. Therefore, at a fixed V_{UG}, the change in MN potential was converted into the change in I_D as shown in Fig. 4. When LG voltage V_{LG} was swept from -4 to -2 V, I_D was abruptly decreased at V_{LG} of -3.5 V because this voltage was threshold voltage of the MTr and electrons in the ER entered the MN. The return of V_{LG} to -4 V caused the hysteresis in I_D because the MTr was turned off and electrons were stored in the MN.

Next, V_{LG} was set to around the threshold voltage with and without IR radiation and electron injection into the MN was monitored as the change in I_D. I_D decreased stepwise with the same height [Fig. 5(a)], and finally flattened with some fluctuation between discrete values [Fig. 5(b)]. This is proof that one electron, which enters the MN from the ER as current leakage of the MTr, is detected as one step of I_D owing to high charge sensitivity of the ETr electrometer. One can see that IR radiation, especially with the shorter wavelength, caused faster injection to the MN. This indicates that the IR signal excited electrons, leading to their injection to the MN. Figure 6(a) shows the IR-power dependences of the reciprocal of the threshold time *t*, which is defined as time when ten electrons entered the MN as shown in Fig. 5(a). The wavelength is 1.5 μm. Linear 1/*t* dependence proves that the IR signal excited the electrons and made the electron injection more frequent. Figure 6(b) plots V_{LG} dependence of 1/*t* with IR signals of 1.3- and 1.5-μm wavelengths and without them. IR signals make 1/*t* larger and the shorter wavelength causes a larger increase of 1/*t*. This would be because the quasi Fermi energy in the ER is increased by IR-induced electron excitation whose energy depends on the wavelength of IR signal [Fig. 2(b)].

Figure 7 shows V_{LG} dependences of 1/*t* when V_{UG} was changed. Higher V_{UG} makes 1/*t* larger at any V_{LG}. This is because higher V_{UG} increases electron density in the ER and thus increases electron injection to the MN. This indicates that the GC can control the IR signal sensitivity using the UG.

4. Conclusions

We demonstrated IR sensing using the Si-based GC, which allows the detection of IR signal absorbed in the small area due to a high-charge-sensitivity electrometer, at room temperature. In addition, the GC allowed the electrical control of the IR sensitivity. Although detection time is still long, it can be improved by optimizing the device structure so that IR signal is absorbed with high efficiency and in a wide area, e.g., an antenna structure. The fabrication is highly compatible with that of Si LSIs, promising the integration of the GC IR sensor and other circuits.

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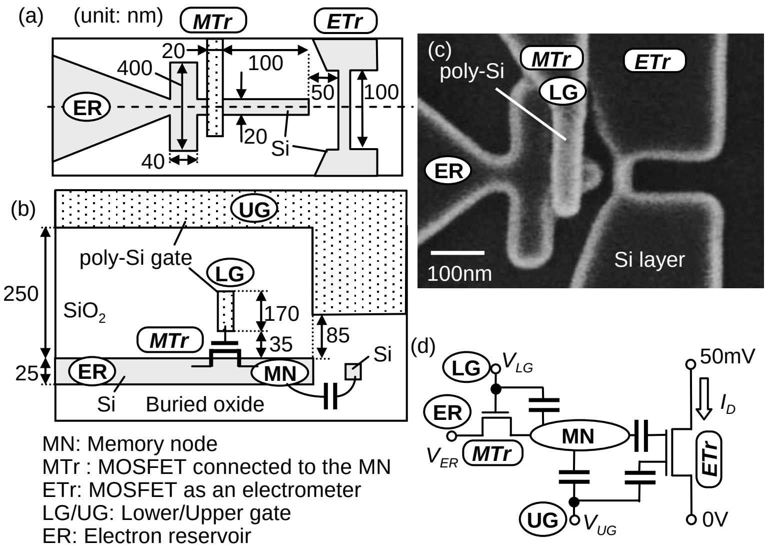

MN: Memory node
MTr : MOSFET connected to the MN
ETr: MOSFET as an electrometer
LG/UG: Lower/Upper gate
ER: Electron reservoir

Fig. 1. (a) Schematic top view of a gain-cell (GC) infrared (IR) sensor. The UG is not shown here. A wider SOI channel, which is on the left of the LG, is patterned in order to increase the number of electrons excited by IR signal. (b) Cross-sectional view along the broken line shown in Fig. (a). (c) Scanning electron microscope image . (d) Equivalent circuit. Voltages for measurements are also shown.

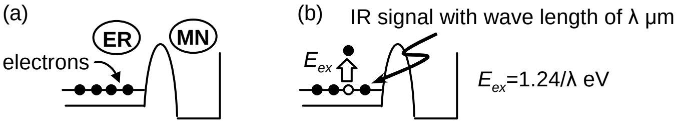

Fig. 2. Energy band diagram in the ER and MN when (a) no IR and (b) IR signals are radiated to the GC sensor.

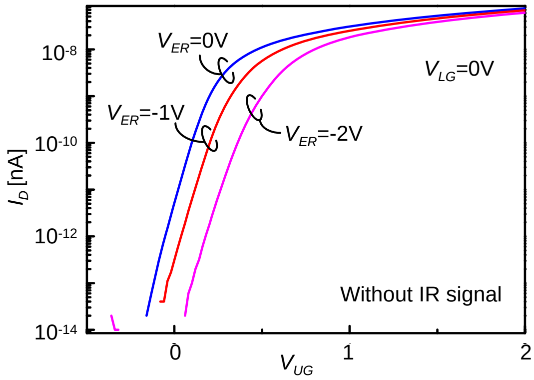

Fig. 3. I_D-V_{UG} characteristics of the ETr at various V_{ER}s. Since the MTr is turned on, change in V_{ER} shifts the curves.

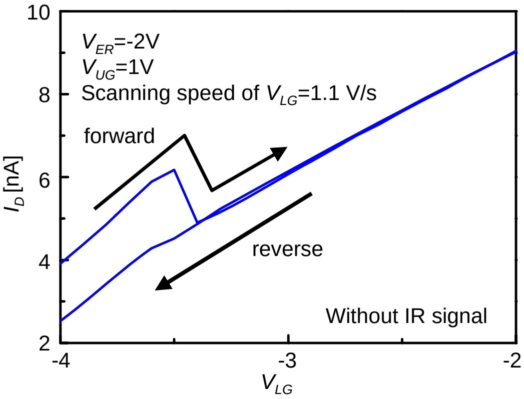

Fig. 4. Hysteresis characteristics of I_D. V_{LG} was changed from -4 to -2 V, and then to -4 V. Abrupt decrease was because the MTr was turned on.

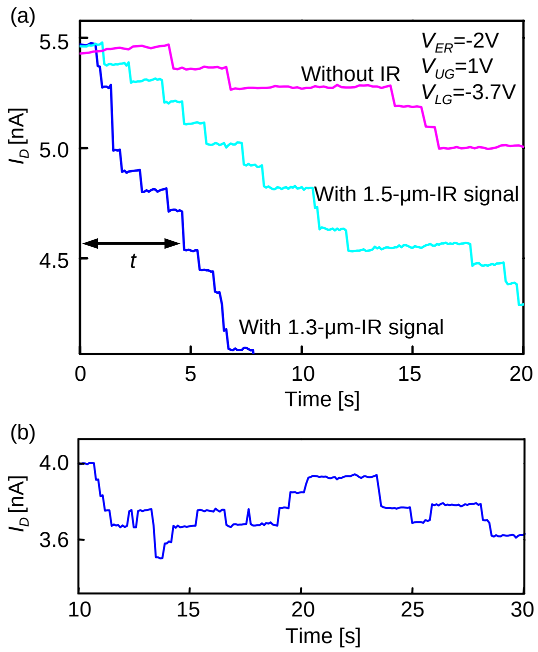

Fig. 5. (a) Change in I_D with and without IR signals. Wavelengths of IR signals were 1.3 and 1.5 μm. IR signal power was 3 μW/cm^2. (b) Change in I_D with IR signal whose wavelength was 1.3 μm.

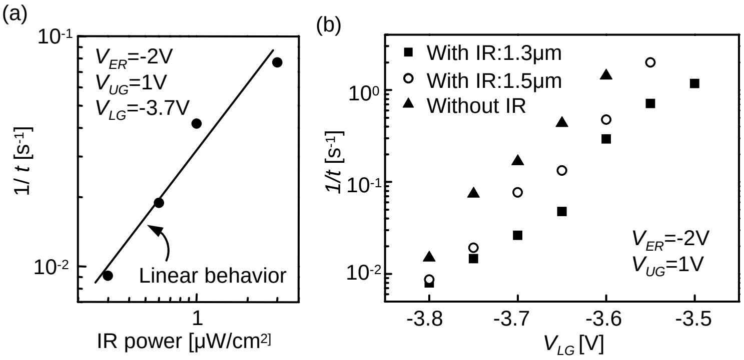

Fig. 6. (a) The dependences of 1/t on IR power at wavelength of 1.5 μm. The t is defined as time when ten electrons enter the MN as shown in Fig. 5(a). (b) The V_{LG} dependences of 1/t with and without IR signals. Wavelengths of IR signals were 1.3 and 1.5 μm. IR signal power was 3 μW/cm^2.

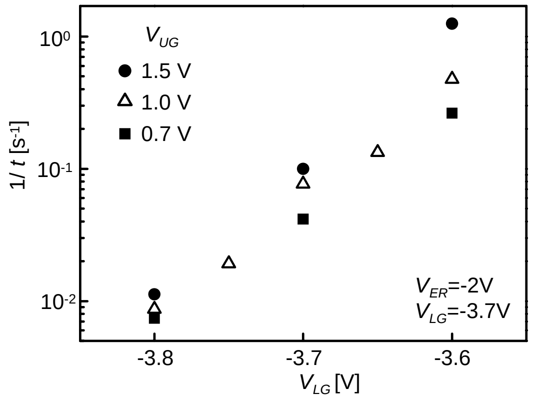

Fig. 7. The V_{LG} dependences of 1/t at various V_{UG}. Wavelength of IR signal was 1.5 μm. IR signal power was 3 μW/cm^2.