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Plasmonic and electronic device-based integrated circuits and their characteristics

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ABSTRACT

This paper presents a plasmonic circuit that has been monolithically integrated with electronic devices on a silicon substrate and then discusses the concept behind this circuit. To form the proposed circuit, two plasmonic waveguides and a detector are integrated with metal–oxide–semiconductor field-effect transistors (MOSFETs) on the substrate. In the circuit, intensity signals or coherent plasmonic signals are generated by coherent light at an operating wavelength at which silicon is transparent, and these signals propagate along the waveguides before they are converted into electrical signals by the detector. These electrical intensity and coherent signals then drive the MOSFETs during both DC and AC operation. The measured performances of the devices indicate that surface plasmon polaritons propagate on the metal surface at the speed of light and drive the electronic devices without any absorption in the silicon.

1. Introduction

High-speed and large-capacity information systems are among the most important infrastructures for human society, both now and in the future, and high-speed integrated circuits (ICs) are indispensable components of these systems. To improve the operating speeds of these ICs while reducing their power dissipation, optical interconnections have been introduced into the circuits. However, the scale of the optical devices that are used is much larger than that of the integrated electronic devices in these ICs, because the propagating light cannot escape the diffraction limit, and the waveguide structures are complex. In contrast, plasmonic devices are simple structures that are not restricted by the light diffraction limit. Plasmonic devices have therefore attracted considerable research attention and have stimulated worldwide development efforts [1–13].

We have previously developed plasmonic devices including waveguides [14,15] and detectors [16–18] for IC applications, and these devices were monolithically integrated with metal–oxide–semiconductor field-effect transistors (MOSFETs) on silicon substrates [19,20]. The surface plasmon polariton (SPP) is easily stimulated by conversion of the propagating light using gratings. The converted SPPs maintain their coherence during propagation on the metal film surface [21] and are hardly affected by the applied electrical bias [15]. SPPs propagating on a metal surface were detected by a plasmonic detector that was constructed using a grating on the metal film. The detector can detect both the coherence and the intensity of these signals [17]. When the detector was fabricated on the gate electrode of a MOSFET (without the plasmonic waveguide), the MOSFET could be driven by the SPPs that were produced by conversion from light propagating in the 1550-nm wavelength band, which is not absorbed by silicon, and the electrical output of the resulting MOSFET was amplified by more than four orders of magnitude [19,20].

In this paper, a new integrated plasmonic circuit comprising multiple plasmonic waveguides, a detector, and two MOSFETs is presented and its circuit performance is studied systematically. These multiple plasmonic waveguides will be important for the construction of future plasmonic networks. The plasmonic device structures are described in Section 2. The integration of the plasmonic devices with the MOSFETs and the resulting circuit performances are then discussed in Section 3. Finally, the results obtained are summarized in Section 4.

2. Integrated circuit components

2.1. Basic concept

Plasmonic devices have been introduced to enable the high density monolithic integration of optical and electronic devices on a

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silicon substrate. The plasmonic devices used in these applications should be simple structures that can be fabricated easily and must operate in a wavelength range at which silicon is transparent to prevent accidental crosstalk being caused by absorption at the substrate or in the electronic devices themselves. Silicon, silicon oxide, and metals are the only materials used to fabricate the proposed ICs using conventional silicon processes, and no other materials or devices were used in these circuits. The plasmonic devices were designed based on the proposed concept using the finite-difference time-domain (FDTD) method and computer-aided design (CAD) and were then fabricated using a 5 µm design rule.

2.2. Plasmonic detector

A Schottky barrier that was built at the interface between the metal and the semiconductor is used to convert the SPPs that are guided to the interface into electrical currents [16,17]. Free electrons that are excited by the SPPs within the metal can cross the barrier, thus resulting in a current if the SPP energy is higher than the Schottky barrier height. A schematic diagram of the detector is shown in Fig. 1. A multi-slit (five- or six-slit) grating structure was introduced to convert incident light into SPPs. A gold film with a thickness of between 200 and 300 nm was deposited on the n-type silicon substrate. Although we used gold as a material of the metal film because of its chemical stability and ease of processing, the plasmonic detector can be fabricated with aluminum instead of gold without lowering the performances. The slit width and pitch were set at 80 nm and 700 nm for the 1.3 µm wavelength band and 100 nm and 840 nm for the 1.55 µm wavelength band, respectively, to enhance detector responsivity [18]. As shown in Fig. 1, the incident light beam partly transmits the grating, and the transmitted light is diffracted at the bottom of the grating. Then, the SPPs are excited at the gold/silicon Schottky interface by coupling with part of the diffracted light from the grating which satisfies the phase matching condition. The SPPs propagate along the gold/silicon interface with decaying their intensities due to ohmic loss in the gold. The propagation lengths calculated from the imaginary parts of the SPP wave vectors are 2.6 µm and 7.1 µm for the 1.3-µm and 1.55-µm free-space wavelengths, respectively. The free electrons in the gold film are excited by the SPPs and then emitted into the semiconductor area over the Schottky barrier. This emitted electrons result in the current flow. The responsivity depends on the SPP energy and it increases as the wavelength of the incident light shortens.

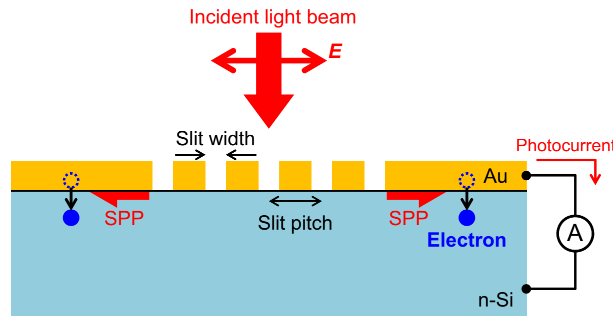

Fig. 1. Schematic diagram of plasmonic detector.

2.3. Plasmonic waveguide

The SPP intensity decreases rapidly during propagation on the metal film surface, but the propagation loss is possibly lower than that of the electrical signal, which is determined by the electrical resistance and capacitance of the waveguide, over short transmission distances [22]. In contrast, the SPP coherence is independent of propagation distance and it remains constant during propagation [21]. In addition to intensity-based signal detection techniques, coherent detection techniques, such as homodyne and heterodyne detection, are useful for plasmonic signal detection applications because the signals are amplified along with the mixing SPPs (light beam). To detect plasmonic signals, the detector that was described in the previous section is set either at the middle or at the end points of the waveguide, at which points the plasmonic signals must be converted into electrical currents. The SPP propagation characteristics were examined using the waveguide structure shown in Fig. 2. As described above, an approximately 200–300-nm-thick gold film was deposited on an n-type silicon substrate, and gratings A and B were then fabricated on this film. A light beam incident on grating A was converted into SPPs on the gold surface via diffraction process. These SPPs then propagated on the gold film, and were coupled into the gold/silicon interface (i.e., the plasmonic detector) at grating B. At this point, the intensities of the coupled SPPs that are propagating along the gold/silicon interface in each direction (SPP_{front} and SPP_{back}) can be controlled to an extent by varying the slit pitch of grating B [14]. These propagation processes were hardly affected by any electrical bias that was applied to either the waveguide or the electrode.

2.4. Integrated plasmonic device

In this study, we developed an integrated plasmonic device that consists of two plasmonic waveguides and a detector. As shown in Fig. 3, the device is composed of a gold film containing three gratings formed on an n-type silicon substrate. The gold surfaces between gratings A and C and gratings B and C act as plasmonic waveguides (and are designated waveguide 1 and 2, respectively), and the gold/silicon interface acts as a plasmonic detector. SPP_A and SPP_B, which are the SPPs that were individually excited at gratings A and B, respectively, propagate toward grating C in opposing directions, and therefore overlap at the gold/silicon interface. A plasmonic beat signal is generated by the interference of SPP_{front} and SPP_{back}.

We deliberately designed the slit pitch of grating C to enhance the intensity of the plasmonic beat signal. The plasmonic beat signal intensity is proportional to the square root of the product of the intensities of SPP_{front} (I_{front}) and SPP_{back} (I_{back}) at the gold/silicon interface. The values of I_{front} and I_{back} for 1.55-µm-wavelength light have been calculated previously for different slit pitches by the FDTD method [14]. Fig. 4 shows the slit pitch dependence of the square root of the above product. As a result, the slit pitch of grating C was set at 580 nm to maximize the plasmonic beat signal intensity. The other structural parameters of grating C were as follows: the slit depth was 300 nm, the slit width was 100 nm, and the number of slits used was two. The slit depth and width were found to satisfy the Fabry–Perot resonance conditions of the SPP mode inside the slit [18–20].

The SPP intensity at the gold/silicon interface in the designed grating was then calculated using the FDTD method to observe the plasmonic beat signal. The schematic diagram of the simulation model is similar to the structure shown in Fig. 3, and an enlarged view of the area around grating C is shown in Fig. 5. The following parameters were used in the simulation. The refractive index values of silicon and gold were set at 3.477 and 0.55 + i11.5, respectively. The wavelengths of the light beams that were incident on gratings A and B were set at 1542.027 nm (194.4145 THz) and 1558.056 nm (192.4145 THz), respectively (i.e., the plasmonic beat signal frequency was set at 2 THz). Then 5-µm-long observation lines were placed at the gold/silicon interface, extending from each slit edge in opposite directions. Fig. 6(a)