Surface Plasmon Devices for Nanoscale Integration with Electronic Device on Silicon

Optical Signal Transmission and Detection through Surface Plasmon on Nanoscale Circuit

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Abstract: This paper discusses the architecture of surface plasmon devices for silicon-based nanoscale-integrated circuits. A suitable structure for surface plasmon devices integrated monolithically with electronic devices is described based on surface plasmon devices fabricated in our group. These devices were fabricated on silicon with conventional CMOS processes. In the devices, light-wave signals are converted into surface plasmon signals with a grating and detected with a Schottky-type diode on a silicon substrate. Both intensity and frequency signals are transmitted along the surface plasmon waveguide in the nanoscale circuit. Such signals were easily amplified with MOSFETs integrated monolithically on the silicon substrate. Here, the wavelength of light used in the circuit is set within the 1550-nm-wavelength band to prevent signals absorption by silicon. This can lead to a simpler structure for waveguides and devices on silicon substrates. These techniques and devices will open a new phase for surface plasmon circuits integrated with electronic devices on silicon substrates.

1 INTRODUCTION

Daily communications are increasingly maintained and supported by optical fibre transmission systems. One of the key components in systems is the electronic device integrated circuit (IC). The progress of such ICs is now, however, saturated because the integration density is approaching scale limits and the signal transmission rate is limited by the wire delay on the silicon substrate. Power dissipation and heat generation are also serious problems. To solve these problems, an optical interconnect has been trialled in ICs. Optical interconnects can eliminate wire delay and heat generation, subsequently, several devices have been developed and proposed in the field of silicon photonics. Here, there is a real possibility that the scale of the interconnect can be further reduced if surface plasmons can be used as signal carriers instead of light.

Recently, various photonic devices using surface plasmons have been developed for many applications (Yatsui et al., 2001; Maier et al., 2002; Nikolajsen et al, 2003; Barnes et al., 2003; Boltasseva et al., 2005). Transmission waveguides (Sergey et al., 2006; Ebbesen st al., 2008; Kim et al., 2008; Verhagen et al., 2009; Aihara et al., 2012) have been developed for signal transmission using surface plasmons. These waveguides are basically thin metal films, but the challenge is to increase the propagation distance of surface plasmons. Long-distant propagation, however, is more difficult for surface plasmons than for propagating light (Boltasseva et al., 2005).

Optical detectors using surface plasmon resonance have also been developed in various wavelength ranges. Some detectors using Schottky barriers were studied and developed in the wavelength range transparent to silicon (Akbari et al., 2010; Fukuda et al., 2010; Casalino et al., 2010; Aihara et al., 2011; Goykham et al., 2012; Hashemi et al., 2013). There is, however, no report on surface plasmon ICs integrated with electronic devices.

In this paper, surface plasmon devices developed in our group are discussed in regard to integrating with electronic devices on a silicon substrate. The surface plasmon devices in our focus are waveguides,

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surface plasmon (light) detectors, and the IC of asurface plasmon detector and MOSFET (Fukuda et al., 2007; Fukuda et al., 2008; Fukuda et al., 2010; Aihara et al., 2011; Fukuhara et al., 2012; Aihara et al., 2012; Aihara et al., 2013; Takeda et al., 2013). The points of discussion are the basic architectures and suitable structures that need to be clarified and proposed for monolithic integration with electronic devices. The basic structure of detectors and waveguides and device integration architectures are discussed in section 2. Device performance and feasibility of integration are presented in section 3. The results are summarized in secton 4.

2 DEVICE INTEGRATION AND ARCHITECTURES

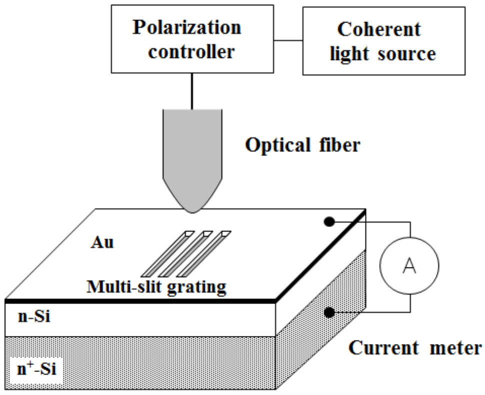
A few factors are important for integrating surface plasmon devices with electronic devices and for merging both types of device on silicon substrates. The factors relevant for surface plasmon devices are:

(1) simple structure and process,
(2) materials: metal and silicon/silicon oxide,
(3) light transparent to silicon,
(4) short signal transmission distance of order below a few hundred nanometres.

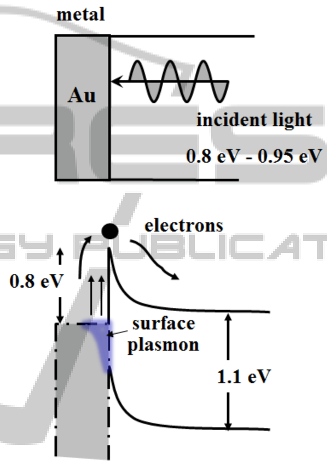
To integrate easily surface plasmon devices with electronic devices on silicon, the surface plasmon devices have to be fabricated using silicon/silicon oxide. The wavelength transparent to silicon are, therefore, favoured as signal carrier waves. Moreover, silicon ICs operate with electrons, and thus signal-carrying light must be converted into electronic signals using silicon photonic devices. In addition, the signals are transmitted along a metal film without any optical waveguide. This structure can control an optical signal using surface plasmons. Simple structures and processes are also important to integrate them on a silicon substrate.

2.1 Optical / Surface Plasmon Detector

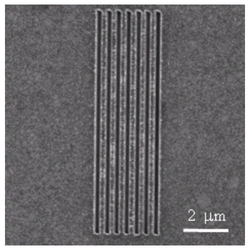
Based on the device architecture just described, we have developed a silicon-based photodetector that monitors optical signals in the wavelength range transparent to silicon. Two types of photodetector, nanoparticle (Fukuda et al., 2010) and grating (Aihara et al., 2011) were developed for this purpose. For our ICs, though, a grating-type photodetector was selected because of its efficiency and process controllability. The basic device structure and operating mechanism are shown in Figure 1.



(a) schematic diagram.



(b) band diagram.



(c) SEM image of a multi-slit grating.

Figure 1: Grating-type surface plasmon detector (photodiode) with a Au/silicon Schottky barrier.

A thin gold film of about a few hundred nanometers was deposited on a silicon substrate, and then grating slits (the width: 150 nm and the pitch: 440 nm for 1550-nm-wavelength light) were fabricated using focused ion-beam etching. At the interface between the gold film and silicon, excited electrons can flow over the barrier when propagating light is incident on the grating. The photocurrent, I_p, is proportional to the square of the energy difference between the incident light and the barrier height as expressed by (Mead and Spitzer, 1963),

$$I_p = A\,(h\nu - \phi_B)^2 \qquad (1)$$

where A is a constant of proportionality, h is the Planck's constant, ν is the incident light frequency, and ϕ_B is the Schottky barrier height. Light of any wavelength is therefore detected if hν is greater than ϕ_B, even if it is transparent to the semiconductor. If the polarization direction of the incident light is in the direction perpendicular to the slits (TM), surface plasmons are excited in the gold film and the amount of electrons crossing over the barrier increases markedly (see Figure 2). This structure can therefore be used as a detector of light and surface plasmons in the wavelength range transparent to silicon. Although the efficiency depends on the wavelength of incident light (see Figure 3), the detector can convert light, and thus surface plasmons, into a photocurrent (or electron flow) of wavelengths roughly below 1600 nm (Fukuda et al., 2010). This range can cover wavelengths used in optical fibre transmission systems. Such detectors can monitor intensity signals as well as frequency signals transmitted by propagating light/surface plasmon. When two light beams having a slightly different frequency (or wavelength) were simultaneously incident on the slits, the beat signal of the two light beams (Figure 4) was monitored with the photodetector using the heterodyne detection technique.

The performance of light and surface plasmon detectors can be improved by introducing suitable structures to the grating (Takeda et al., 2013; Aihara et al., 2013).

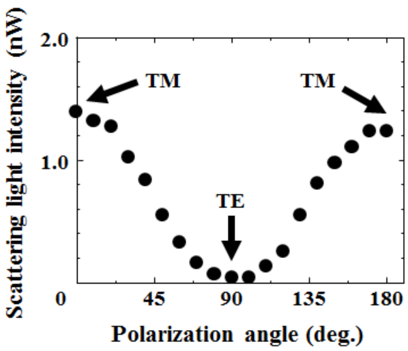


Figure 2: Polarization dependence of the photocurrent in a light and surface plasmon detector. TM and TE indicate the incident light polarization, i.e. perpendicular and parallel respectively to the slit. The polarization angle at 0 degree is set at the polarization perpendicular to the slit (TM).

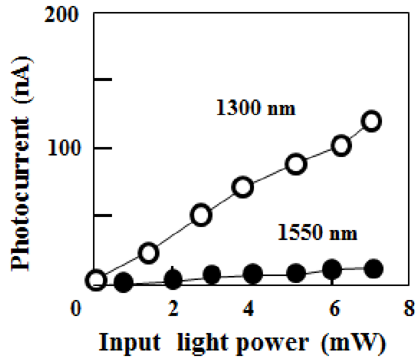


Figure 3: Wavelength dependence of the photocurrent in a gold thin film/silicon Schottky barrier. The conversion rate was about 17 nA/mW for 1300 nm and 1.7 nA/mW for 1550 nm.

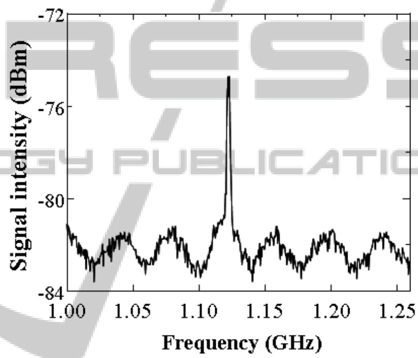


Figure 4: Beat signal detected with the photodetector.

2.2 Surface Plasmon Waveguide

To interconnect surface plasmon and electronic devices and to transmit signals, surface plasmon waveguides are indispensable. The target distance for signal transmission is less than a few hundred nanometres; if greater transmission distances are required, propagating light should be used because the propagating loss of surface plasmon is quite large.

Waveguide structures are essentially divided into two types depending on the type of surface plasmon, propagating or localized. Both types of waveguide could transmit optical intensity and frequency signals. These waveguides are described and discussed in this sub-section.

2.2.1 Propagating Surface Plasmons

This type of surface plasmon propagates along a continuous metal film at a speed determined by the dielectric constant of the medium. The transmission property enables the propagation of surface plasmon to be controlled with a simple waveguide structure deposited on the silicon substrate. This is a big advantage when compared with that of propagating light which requires a complicated waveguide structure.

The transmitting length closely depends on the structure and material of the metal film. The transmission loss, caused by electron scattering in metal (Ohmic loss), can be large (see Figure 5) (Aihara et al., 2012). The transmission loss is, however, acceptable if the distance is less than a few hundred nanometres. This transmission distance will be sufficient to interconnect plasmonic and electronic devices. Although the quality and structure of the metal film strongly influences the transmission loss, the metal waveguide can be easily fabricated on a silicon wafer without any special equipment.

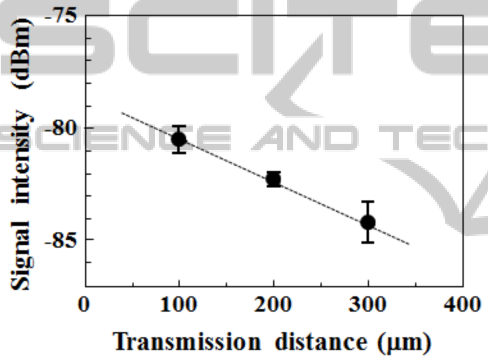
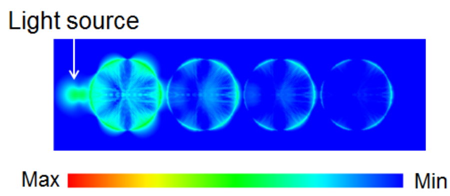


Figure 5: Loss characteristics of surface plasmons during transmission on gold film.

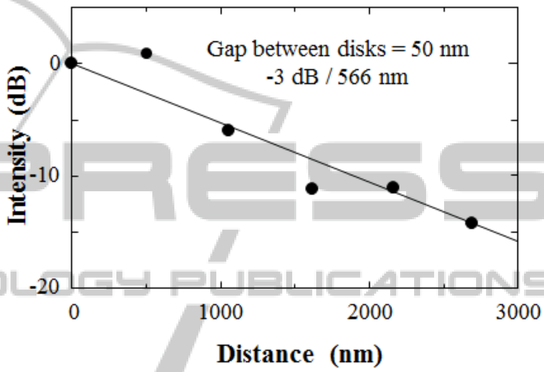
2.2.2 Localized Surface Plasmons

The waveguides for this type of surface plasmon are not continuous metal films but chains of metal disks spaced a few ten nanometres. This structure is useful as it electrically disconnects the IC, although the loss is much larger than that of a continuous metal waveguide. The surface plasmon at a disk can induce surface plasmon resonances at the neighbouring disk if the chain is set to operate at a frequency of the surface plasmon resonance. This behaviour can be continuously transmitted along the chain, and a signal can be transmitted.

The chain of disks was designed specifically as a waveguide for localized surface plasmons. Its transmission loss was estimated using the finite-different time-domain (FDTD) method; see Figure 6 (Fukuhara et al., 2012). Each disk is gold film with 500-nm in diameter and 100-nm thick; the separation between disks is set at 50 nm. A light source of wavelength of 1500 nm is set near the first disk of the chain. A localized surface plasmon is induced at the first disk which is then transmitted to the adjacent disk. Thus, this structure is able to transmit optical signals converted from incident light by surface plasmons.



(a) Calculation model.



(b) Intensity change as a function of distance.

Figure 6: Calculation result of intensity variation during surface plasmon transmission on a chain of nanoscale gold disks.

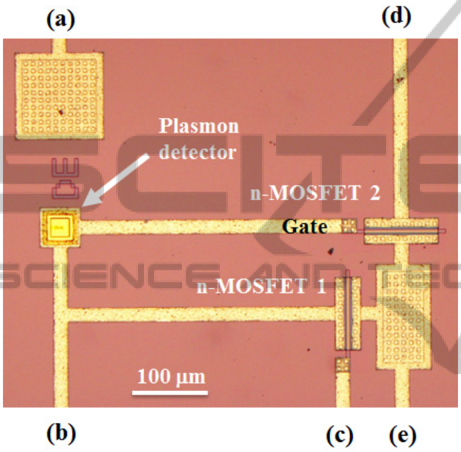
2.2.3 Signal Transmission through Surface Plasmons

Intensity signal transmission has been confirmed on both the continuous-metal and chain-type waveguides (Fukuhara et al., 2012; Aihara et al., 2012). The transmission distance for both is limited by Ohmic loss. An optical frequency signal was also transmitted along the continuous gold film without any coherence degradation (Aihara et al., 2012). For a chain of disks, the transmission of an optical frequency signal was estimated using FDTD simulation. From these results, it can be said that the intensity and frequency signals are transmitted through surface plasmons over a nanoscale surface plasmon circuit on a silicon substrate.

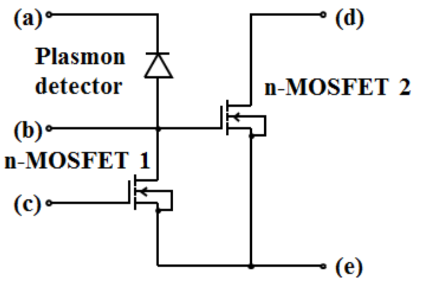
As described, the surface plasmon is controlled with a simple metal waveguide after conversion from propagating light. This controllability is enabled using silicon's transparency range to light.

3 DEVICE INTEGRATION

Based on the architecture discussed in section 2, a part of the devices developed was monolithically integrated with electronic devices onto silicon substrates. One example is shown in Figure 7 (Aihara et al., 2013). The surface plasmon (or light) detector is set on the gate electrode of a MOSFET. This surface plasmon detector and two MOSFETs IC operated well under DC- and AC-bias, and a photocurrent converted from incident light through surface plasmons was electrically amplified.



(a) optical micrograph of the top view.



(b) circuit diagram.

Figure 7: An integrated circuit of a surface plasmon detector and two MOSFETs.

4 CONCLUSIONS

Using architectures for surface plasmon devices developed in our group, some suitable structures of surface plasmon devices have been discussed for monolithic integration with electronic devices on a silicon substrate. In the devices, surface plasmons transparent to silicon were used to prevent absorption by silicon, and the use of transparent light with metal waveguides enables easy control of these surface plasmons. These techniques allow integration of surface plasmon devices with electronic devices using standard CMOS process. The device integration opens a new phase for nanoscale surface plasmon ICs.

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REFERENCES

Aihara, T, Nakagawa, K. Fukuhara, M, Yu, Y. L, Yamaguchi, K, Fukuda, M. (2011) Optical frequency signal detection through surface plsmon polaritons. *Appl. Phys. Lett.* 99, 043111-1-043000-3.

Aihara, T, Fukuda. M. (2012) Observation of plasmonic frequency-modulated signal transmission. In *IEEE Optical MEMS & Nanophotonics 2012* (65) Alberta, Canada. IEEE.

Aihara, T, Fukuda. M. (2012) Transmission properties of surface-plsmon-polariton coherence. *Appl. Phys. Lett.* 100, 213115-1-213115-4.

Aihara, T, Fukuhara, M, Takeda, A, Futagawa, M, ¿??, Sawada, K. Fukuda, M. (2013) Monolithic Integration of surface plasmon detector and metal-oxide-semiconductor field-effect transistors. *IEEE Photonics J.* 5, 6800609.

Akbari, A, Tait, R. N, Berini, P. (2010) Surface plasmon waveguide Schottky detector. Opt. Express 18, 8505-8514.

Barnes, W. L, Dereux, A, Ebbesen, T. W. (2003) Surface plasmon subwavelength optics. *Nature* 424, 824–830.

Boltasseva, A, Nikolajsen, T, Leosson, K, Kjaer, K, Larsen, M. S, Bozhevolnyi, S. I. (2005) Integrated optical components utilizing long-range surface plasmon polaritons. *J. Lightwave Technol.* 23, 413-422.

Sergey, I, Bozhevolnyi, Valentyn, S, Volkov, Devaux, E, Laluet, J. –Y, Ebbesen, T. W. (2006) Channel Plasmon subwavelength waveguide components including interferometers and ring resonators. *Nature* 440, 508-511.

Casalino, M, Sirleto, L, Lodice, M, Saffioti, N, Gioffre, M, Rendina, I, Coppola, G. (2010) Cu/p-Si Schottky barrier-based near infrared photodetector integrated with a silicon-on-insulator waveguide. Appl. Phys. Lett. 96, 241112-1-241112-3.

Ebbesen, T. W, Genet, C, Boshevolnyi, S. I. (2008) Surface Plasmon circuitry. Phys. Today, May, 44-50.

Fukuda, M, Yamasaki, Y, Oota, N, Utsumi, A. (2007) Optical near-field generation and detection by using metal-dielectric film fabricated from silver paste and spherical fused silica. *IEEE Photon. Technol. Lett.* 19, 1160-1162.

Fukuda, M, Utsumi, A, Funato, H, Tohyama, M, Takemoto, N, Yamamoto, S, Yamasaki, Y, Tanabe, T. (2008) Performance of Random Metal-dielectric film on optical signal transmission. *IEEE Photon. Technol. Lett.* 20, 590-592.

Fukuda, M, Aihara, T, Yamaguchi, K, Ling, Y. Y, Miyaji, K, Tohyama, M. (2010) Light detection enhanced by surface plasmon resonance in metal film. *Appl. Phys. Lett.* 96, 153107-1-153107-3.

Fukuhara, M, Aihara, T, Ushii, Y., Fukuda, M. (2012) Optical frequency signal transmission via localized surface plasmons. In *IEEE Photonics Conference 2012* (23- 27) Burlingame. IEEE.

Goykhman, I, Desiatov, B, Khurgin, J, Shappir, J, Levy, U. (2012) Waveguide based compact silicon Schottky photodetector with enhances responsivity in the telecom spectral band. Opt. Express 20, 28594-28602.

Hashemi, M, Farzad, M. H, Mortensen, N. A, Ziao, S. (2013) Enhance plasmonc light absorption for silicon Schottky-barrier photodetectors. Plasmoncs 8, 1059-1064.

Kim, J. T, Ju, J. J, Park, S, Kim, M. –S, Park, S. K, Lee, M. –H. (2008) Chip-to-chip optical interconnect using gold long-range surface plasmon polariton waveguides. Opt. Express 16, 13133-13138.

Maier, S. A, Kik, P. G, Atwater, A. (2002) Observation of coupled plasmon-polariton modes in Au nanoparticle chain waveguides of different lengths: Estimation of waveguide loss. *Appl. Phys. Lett.* 81, 1714–1716.

Mead, C. A, Spitzer, W. G, (1963) Photoemission from Au and Cu into CdS . *Appl. Phys. Lett.*, **2**, 74-75.

Nikolajsen, T, Leosson, K, Salakhutdinov, I, Bozhevolnyi, S. I. (2003) Polymer-based surface plasmon-polariton stripe waveguides at telecommunication wavelengths. *Appl. Phys. Lett.* 82, 668–670.

Takeda, A, Aihara, T, Fukuhara, M, Ishii, Y, Fukuda, M. (2013) Optimal design of photodetector with multi-slit grating. In *IEEE Optical MEMS & Nanophotonics 2013* Kanazawa, Japan. IEEE (accepted).

Verhagen, E, Spasenovic, M, Polman, A, Kuipers, L. (2009) Nanowire Plasmon excitation by adiabatic mode transformation. *Phys. Rev. Lett*. 102, 203904-1-203904-4.

Yatsui, T, Kourogi, M, Ohtsu, M. (2001) Plasmon waveguide for optical far/near-field conversion. *Appl. Phys. Lett.* 79, 4583–4585.