計測自動制御学会東北支部40周年記念学術講演会
2004 年12 月22 日，23 日　日本大学工学部

講演番号：A09

超小型血流センサーを用いた血流の変化の測定

森田　巧　　坂野　進[1]

Integrated Blood Flowmeter Using Micromachining Technology

Takumi Morita, Susumu Sakano

[1]*College of Engineering, Nihon University*

1 Nakagawara-Tokusada , Tamura-cho, Koriyama , 963-8642 , Japan

Tel: +81 24 956 8774,Fax: +81 24 956 8860, E-mail: sakano@mech.ce.nihon-u.ac.jp

Abstract- The micro machining technology has been advanced on the basis of the semiconductor manufacturing technology. In this study, the research on the manufacturing the integrated micro optical sensor accumulated LD and PD on the semiconductor substrate is practiced. The fabrication method is the technology of photolithography and etching technology in the semiconductor manufacturing. The blood flow meter is taken up as a typical application of the micro optical sensor.

1. Introduction

Wearable devices that gather physiological information are highly demanded for bedside monitoring in hospitals, telenursing for elderly people living alone at home, and long-term health assessments to predict and prevent adult diseases, and several wearable devices in finger-ring or wristwatch configurations have been developed. However, the incorporated sensors are restricted to either pulse-wave types or pulse oximeters containing light-emitting diodes [1]. In these applications, it is most important that the sensors are small and light so that they can be worn comfortably.

This paper discusses a new design for a very small lightweight blood flowmeter that permits real-time monitoring of capillary microcirculation for a wearable health monitoring system. The hybrid-integrated structure includes an InGaAsP/InP distributed feedback laser diode (DFB LD) with a wavelength of 1310 nm, an edge-illuminated photodiode (PD) and polyimide waveguides on silicon substrate (2 × 3 mm^2). This flowmeter is much smaller than a previously reported compact one in which a packaged semiconductor laser is mounted together with the detectors in a small probe.In-vivo experiments concerning blood perfusion in a finger capillary confirm the feasibility of the blood flow meter.

2. Structure of Sensor

2.1 Conventional blood measurement Blood flow measurements have been of special interest for many years because they offer a promising tool for the noninvasive examination of the physiological state of the microcirculation. Impaired blood circulation is a factor deeply involved in the etiologies of many adult diseases. The first application of laser Doppler velocimetry to blood flow was reported by Riva et al [2]. In 1975, Stern demonstrated that scattered light from laser-illuminated skin is Doppler broadened and that the Doppler width correlates with blood flow [3]. There are a number of ways to implement blood flowmetry and some of those have been put into clinical use. The most common technique involves the use of optical fibers to conduct the He-Ne laser light or laser diode (LD) light to the skin tissue and from the tissue to a photodetector [4-5]. However, the instrument requires positioning and alignment of individual optical components (such as lens

and fiber) in three dimensions. As a result, the whole instrument becomes bulky with dimensions of several ten centimeters, although the probes are small. Such a large instrument is not suitable as wearable devices. Furthermore, movement of the fiber affects the output signal [6].

2.2 Structure LD (Laser Diode), PD (Photo Diode) and wave guide are constructed on the silicon substrate. In general, LD, PD are formed directly on the silicon substrate. Though the mass production of the micro optical sensor is possible, there are problems in the dispersion of the reliability and functional properties of the manufactured sensors as mentioned above. The LD and PD for the optical communication are used in this study. They have long life and high reliability, and small fluctuation of the properties. LD and PD are bonded on the silicon substrate and the polyimide light waveguide for the light scatters is formed using photolithography technology. The effect of the external light from the outside must be avoided in the optical sensor.

3. Fabrication Method

The micro optical sensor is manufactured by forming the patterns on the silicon substrate and LD, PD are bonded on the silicon platform. It is shown in Figure. 1. The passive alignment technique using alignment mask is used for accurately bonding LD and PD onto silicon platform ($3\times 2mm^2$). LD is a DFB LD with a wavelength of 1310 nm and PD is an edge-illuminated refracting-facet PD with a small active area. LD has the lifetime of more than several hundred thousand hours and reasonable wavelength stability with the temperature. The polyimide waveguide is formed on the silicon platform. The convex shaped edge is formed in the polyimide waveguide for collimating the laser beam from LD horizontally.

4. Measurement Principle

A schematic diagram of the proposed integrated laser Doppler blood flowmeter and a cross section of blood circulation in the skin are shown in Fig. 2. Skin is illuminated with a coherent light source (DFB LD).

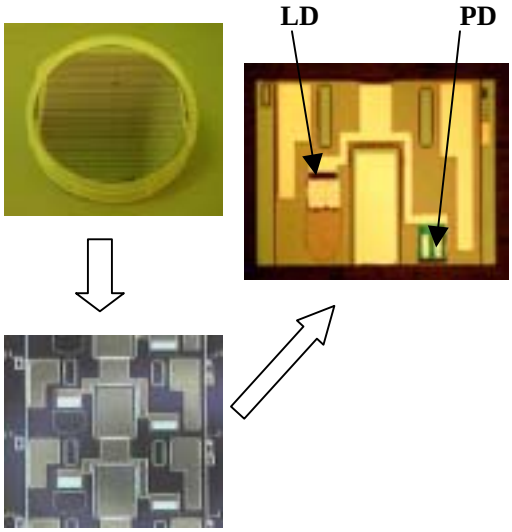

Fig. 1. Fabrication of optical sensor

The light is scattered by the tissue and backscattered light is collected on the detector (PD). A small part of the light is scattered by moving particles (mostly red blood cells) in the capillaries of a sample volume of tissue and is Doppler shifted. This Doppler-shifted light and the non-Doppler-shifted light scattered by nonmoving structures of the tissue interfere at the detector, which causes intensity modulations. The Doppler frequency spectrum to be measured at the detector, in the case of a single velocity value, peaks at the frequency corresponding with the velocity. In the case of scattering from tissue, it will have an approximately exponential decay in the spectral domain because of the random character of the velocity vector of the blood perfusion in the capillaries (Red blood cells move in different directions and at different velocities) and because of multiple scattering in the tissue. It has been shown that in such cases the first moment $\langle\omega\rangle$ of the power spectrum $S(\omega)$ of the frequency distribution of all possible Doppler frequencies, given by

$$\langle\omega\rangle = \int \omega \cdot S(\omega) \cdot d\omega, \qquad (1)$$

is proportional to the averaged velocity times the concentration of Doppler scattering particles, i.e., to the flow of particles. We used a digital signal processor unit (Online Applications Systems Corporation) to derive the first moment $\langle\omega\rangle$ (the flow of the blood flow) as continuous output

signals.

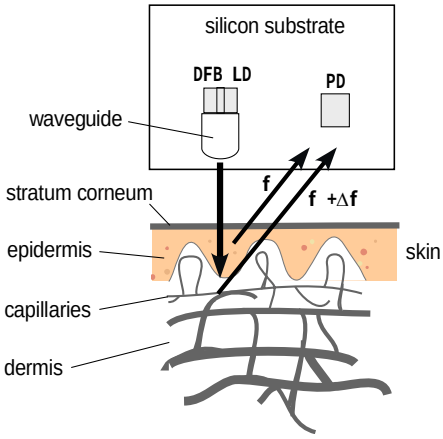

Fig.2. Blood flowmeter and cross section in the skin

5. Integrated Blood Flowmeter

We designed the small sensor structure integrated with the LD and PD without fibers. Figure 3 is a schematic diagram of the proposed blood flowmeter. The device consists of only a LD, PD, fluorinated polyimide wave guide, and silicon cap on the same silicon platform (2 × 3 mm^2), which functions as an optical bench and a heat sink. An InGaAsP/InP DFB LD with a wavelength of 1310 nm, a power of 5 mW, and a threshold current value of I_{th} = 10 mA ware used as a light source. In the conventional instruments, visible light (600-800 nm) is mainly used. However, we chose near-infrared laser (wavelength of 1310 nm) because of the very high transmittance at 1310 nm , although there is some small absorption of water. This high penetration is due to the low absorption and scattering coefficients of the tissue at this wavelength. In the wavelength region of 350-1200 nm, melanin is the major absorber of radiation in the epidermis, especially at shorter wavelength. We can expect that a near-infrared laser may make measurements in deeper lying blood vessels, where blood flow is higher. Our InGaAsP/InP DFB LD has a lifetime of more than several hundred thousand hours. Forming a convex-shaped edge in the waveguide eliminated the need for a lens. This collimates the laser beam horizontally. The full-width at half-maximum (FWHM) of the horizontal far-field pattern (FFP) was smaller than 1°. We used an edge-illuminated refracting-facet PD (responsively: 0.91 A/W, dark current: 0.03-0.28 nA) as a detector. In a conventional flowmeter, a spatial filter, such as a pinhole or a slit, or an optical fiber is normally placed in front of the PD to pick up the time-varying laser speckle, which is produced by the scattered light from the tissue [12, 13]. On the other hand, in our flowmeter, by using a PD with light-sensitive area of 15 m ×65 m, we eliminated the need for such additional components. The absence of optical fibers rules out disturbances due to movement artifacts in the signal.

The silicon cap, which has titanium deposited (thickness: 200 nm) on its inner wall, prevents light emitted from the backside facet of the LD and scatteredfrom the edge of the waveguide.

6. Blood Perfusion Measurement

We performed some measurements of blood perfusion from the fingertip of some volunteers. The fabricated device was attached directly to the fingertip with minimum pressure.

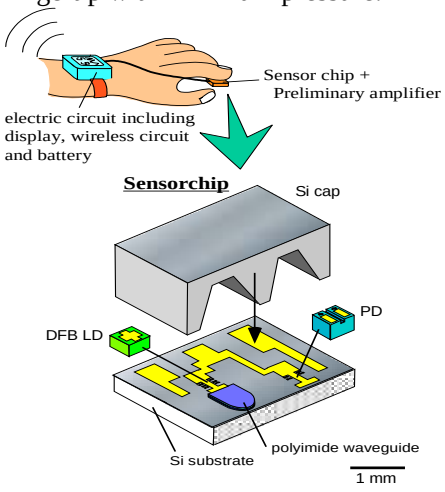

Fig.3. Proposed laser blood flowmeter

In order to test the dynamic response of microcirculation, the upper arm was occluded with a pressurized cuff. Fig. 4 shows a typical flow signal [Eq. (1)] as a function of time (laser power: 3.5 mW). It is clearly seen that upon occlusion with the pressurized cuff inflated to 200 mmHg there is a rapid drop in the flow signal, indicating poor circulation. The flow signal shows small variations with the heartbeat. The heartbeat frequency is easily distinguished in the signals, except for the sections with

occlusion. This signal is in agreement with that is obtained by a commercially available laser Doppler flowmeter (Cyber Med CDF-1000, Online Applications Systems Corporation). A typical example is shown in Fig. 5. We see that the signal spectrum obtained changes much depending on smoking. We can also see abrupt occurrence of a low-frequency signal. With this portable micro sensor, we can obtain such data immediately by carrying this.

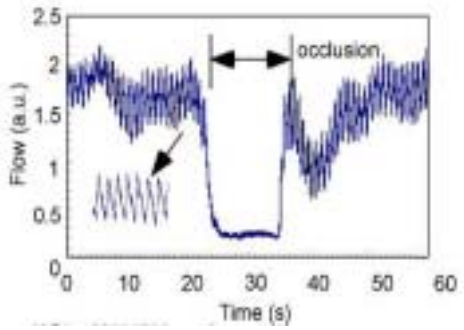

Fig. 4. Flow signal of fingertip

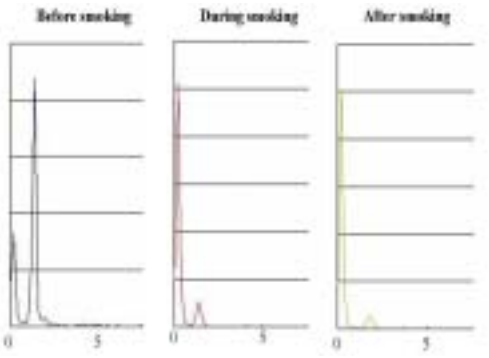

Fig. 5. Variation of frequency spectrum

7. Conclusions

We have constructed an integrated laser blood flowmeter by micro machining and surface mounting techniques. The device is 1.5 mm thick × 2 mm wide × 3 mm long. Using this flowmeter, we performed in-vivo measurement of blood perfusion in the fingertip. Because of its small size together with its high performance, this integrated blood flowmeter can be easily handled in clinical situations and has great potential for a wearable health monitoring system. Further developments, especially miniaturization of the electronic circuit, are in progress.

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