Abstract. We carried out non-contacting measurements of photocurrent distributions in GaN blue light emitting diode (LED) chips using our newly developed ultraviolet (UV) laser SQUID microscope. The UV light generates the photocurrent, and then the photocurrent induces small magnetic fields around the chip. An off-axis arranged HTS-SQUID magnetometer is employed to detect a vector magnetic field whose typical amplitude is several hundred femto-tesla. Generally, it is difficult to obtain Ohmic contacts for p-type GaN because of the low hole concentration in the p-type epitaxial layer and the lack of any available metal with a higher work function compared with the p-type GaN. Therefore, a traditional probe-contacted electrical test is difficult to conduct for wide band gap semiconductors without an adequately annealed electrode. Using the UV-laser SQUID microscope, the photocurrent can be measured without any electrical contact. We show the photocurrent vector map which was reconstructed from measured magnetic fields data. We also demonstrate how we found the position of a defect of the electrical short circuits in the LED chip.

1. Introduction

Generally, the spatial resolution of the SQUID magnetometer was determined by the larger of either the diameter of the SQUID or the SQUID-to-sample distance. Coexistence of the high spatial resolution with high sensitivity was difficult. This restriction can be drastically improved by combining a laser and SQUID. Using the laser SQUID microscope, since the spatial resolution is of comparable size to the spread area of the excitation source, it achieves micrometer-scale photo-magnetic images. Furthermore, since phase detection can be used in such an active measurement, it is easy to extract signals without being influenced by the environmental noise, unlike in passive measurement. We have demonstrated contact-less testing for a silicon semiconductor device using a near-infrared laser SQUID microscope [1-4]. Similar research was reported by Shurig et al. [5-7] and Nikawa et al. [8, 9]. We report here on an ultraviolet laser SQUID microscope to test the GaN-LED, in which it is difficult to measure the current even when using the contacting method, due to the existence of the surface potential barrier. The photocurrent distribution in the sample chip is visualized in this paper.

2. Laser SQUID microscope for GaN LED

GaN is a wide-band-gap semiconductor with $E_g = 3.5$ eV of band gaps. GaN emits blue light and is used for blue LED, or white LED combined with a fluorescent substance. Inspection technology will
become more important since the expansion of use of the white LED as a household light source is expected in the near future. For a wide-band-gap semiconductor, especially in the p-type, the Fermi level becomes deep and the work function becomes very large. In order to obtain the Ohmic contact for a p-type semiconductor, the work function of the electrode metal should be larger than that of the p-type semiconductor. Many attempts have been made so far to find a way of lowering contact resistivity on p-GaN. The Ni-based metal scheme was commonly adapted for Ohmic contacts on p-type GaN in LED. The Schottky barrier height was effectively reduced by p-NiO [10, 11]. In any case, high temperature (~500 K) annealing is needed for low contact resistivity. As a practical matter, making an electrical measurement by a contact probe is difficult without adequately prepared electrodes. Moreover, mechanical contacts cause contamination and scratches. Therefore, measurement methods involving wafer contact cannot be used to monitor product wafers during the manufacturing process.

Using the laser SQUID microscope, the energy given to the sample is supplied by a laser without contact. Optical energy is transformed into current according to the inherent photovoltaic characteristic of the semiconductor. When the semiconductor is illuminated by the laser beam (hv > Eg), an electron-hole pair is generated, and then the electron-hole pair is separated by the electric field in the depletion layer. Since excess carriers cannot flow out from the boundary of the chip, the excess carriers recombine within the chip, the photocurrent is closed inside the sample, and magnetic fields are generated. The problem of the Schottky barrier between electrodes and the sample is thus avoided.

The Electron Beam Induced Current (EBIC) [12] is a method for measuring the current excited by an electron beam in semiconductors and is commonly used. In the EBIC, the vacuum and an electrical contact to ground are required, and there is a charging problem if an isolation layer exists.

3. Experimental Procedures

Fig. 1 shows the setup of the experimental apparatus. A linear polarized He-Cd gas laser having a wavelength of 325 nm and power of 20 mW were used as an excitation light source. The CW laser was modulated by an external optical chopper for the purpose of lock-in detection. A modulation frequency of 3.07 kHz was selected. The time-averaged laser power measured at the sample surface was 2.2 mW. The laser unit and the optical chopper were placed outside a magnetically shielded box.

A high temperature superconductor (HTS)-SQUID magnetometer with noise less than 80 fT/Hz^{1/2} was employed for this system. The diameter of the SQUID sensor was 8 mm and the material was YBCO. The SQUID was cooled by liquid nitrogen in a fiberglass dewar. The SQUID was horizontally shifted about 5 mm from the laser focus, thus making an off-axis arrangement. The vertical distance between SQUID and the sample was about 11 mm, including the wafer thickness.

The sample wafer was mounted on an XY stage, and the magnetic field distribution image was obtained by a 2-dimensional scan. A magnetic motor-driven XY stage was used. The motor section was shielded by a permalloy plate. A 150 mm-high non-magnetic spacer was also placed between the wafer and stage surface, and the motor and SQUID were separated by a sufficient distance to maintain flux locking controlled by the flux locked loop (FLL) circuit. The magnetic field was measured within a time period when the motor was not moving. The sampling interval was 12 µm, and the laser’s spot diameter was 20 µm. The adjacent data had overlapping laser illumination areas. The sample was a GaN blue LED chip on a 2” sapphire wafer, upon which had been performed metals deposition, etching of electrodes and annealing. The dimension of the chip was 350 x 340 µm and each chip was electrically isolated by a scribing groove. The laser beam was illuminated from the GaN epitaxial surface.

Measurements were taken within a double permalloy layer magnetic shielded box. The magnetic shield ratio was -40 dB for static fields. Since it is the active type measurement method which gives an excitation signal and measures the magnetic response, a massive magnetic shield is not necessary. The lock-in detection was performed at the modulation frequency. The measurement time in each sampling point was 6 s with the time constant of the lock-in amplifier of 300 ms. Data acquisition and stage control were performed automatically by PC.

Fig. 2 shows the position of SQUID and a laser focal. The magnetic field was measured by two points which intersected perpendicularly to the laser focal position. Although the SQUID we used was
only 1 channel, vector magnetic fields can be measured by shifting SQUID along the X-axis or Y-axis alternatively. By using off-axis configurations, even if the photocurrents flow concentrically from the laser focal center, magnetic fields are detectable. The detectable magnetic field vector component was \( B_z \) in our setup, which is normal to the surface of the sample.

Since the modulation frequency was sufficiently lower than the frequency response of the LED, the phase polarity of lock-in detection would correspond to the direction of a magnetic field. The photocurrent direction was determined by the phase polarity of the lock-in output. The photocurrent vector was calculated by the Biot-Savart law with the assumption that the measured magnetic field was generated from a current vector which passes through a laser focal area. The finite length of the current vector in the laser focal area was set equal to the sampling interval of 12 \( \mu \text{m} \).

**Figure 1.** Setup of the experimental apparatus. FG: function generator, DM: dichroic mirror, HM1: detachable half mirror, HM2: half mirror, PM: power meter, WLS: white light source, FLL: flux locked loop, MSB: magnetically shielded box, PC: personal computer, CCD: charge-coupled device camera.

**Figure 2.** Position of SQUID and laser focal.

### 4. Results

The measured samples were defective chips of which the p-n junction short circuits by a metal residual. The residual metal accidentally remained on the edge of the p-n junction during the etching of the electrodes. The size of the residual metal was 1 \( \mu \text{m} \) to 10 \( \mu \text{m} \) depending on the chips. All chips in the wafer were inspected by the conventional contacting method in advance to conform the short-circuit. Note that the sample used in this experiment was finished until electrode formation, but that the electrodes are not necessary for the laser SQUID microscope if the sample has a p-n junction.

Figure 3(a) shows the photocurrent distribution calculated from the two magnetic field components. A photograph of the defective chip taken by a built-in optical microscope is also shown in figure 3(b) for reference. When a short-circuit exists in a chip, the photocurrent concentrates at the position of the short-circuit. When approaching the short-circuit position, the amplitude of the photocurrent decreases because the magnetic fields cancel each other. There were 9 short-circuit chips in the sample wafer, and the current distribution of all their chips was concentrated in the short position. The exact position of the short circuit in the chip can be found without any electrical contact.
Figure 3. (a) Photocurrent distribution map in a GaN LED chip which has a short circuit in the upper right corner. (b) Photograph of the defective chip taken by optical microscope in the dashed line area of figure 3 (a).

Here, the magnetic field distribution measured by scanning and magnetic fields was not simultaneously measured at all sampling points. That is, the calculated current shown in figure 3(a) is not flowing by such distribution simultaneously, and there is no continuity of currents. The magnetic field measured by the UV laser SQUID microscope is an averaged result of the vector addition of each magnetic field that is generated from the closed-loop photocurrent distributions in the whole chip.

5. Conclusion

The ultraviolet laser SQUID microscope was developed to visualize photocurrent distributions in the GaN-LED chip. An ultraviolet laser illuminates the chip and the photocurrent vector is measured by an off-axis arranged HTS-SQUID magnetometer. When a short circuit exists in the chip, the photocurrent concentrates at the position of the short circuit. It is difficult to obtain Ohmic contacts for p-type GaN, however, UV laser SQUID microscope are able to measure photocurrents without electrical contacts. This method will be effective for nondestructive testing of wide-band-gap semiconductors.

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