Journal of the Optical Society of Korea, Vol. 3, No. 1, March 1999, pp. 27-31

# Visible wavelength autocorrelation based on the two-photon absorption in a SiC photodiode

Young-Chul Noh, Jai-Hyung Lee, and Joon-Sung Chang

*Department of Physics, Seoul National University, Seoul 151-742, KOREA*

Yong-Sik Lim

*Department of Applied Physics, Kon-Kuk University, Chungju 380-701, KOREA*

*E-mail : yslim@kcucc.cj.konkuk.ac.kr*

Jong-Dae Park

*Department of Physics, Pai-Chai University, Taejon 302-735, KOREA*

(Received November 17, 1998)

The two-photon absorption of a SiC photodiode was utilized to obtain autocorrelation signals of the pulses from a mode-locked Rh6G dye laser. The autocorrelation signals were in good agreement with those obtained by a conventional autocorrelator using a second harmonic crystal and photomultiplier tube. The sensitivity of the autocorrelator with the SiC photodiode was about $4 \times 10^3$ $(mW)^2$. From these results it was demonstrated that the SiC photodiode is suitable as a nonlinear device for an autocorrelation measurement in the visible range.

## I. INTRODUCTION

During the last two decades there has been rapid progress in the development of ultrashort pulse lasers. Now in numerous laboratories the ultrashort pulse lasers are employed for research and applications, resulting in an increased demand for convenient methods of ultrashort pulse characterization. An optical autocorrelation based on a Michelson interferometer has most commonly been used for the diagnosis of the pulses from a mode-locked laser. Conventionally, the Michelson interferometer splits the optical pulse into two replicas with a relative time delay and recombines them for second harmonic generation (SHG) at a nonlinear crystal. In order to record the autocorrelation signal the SHG signal has usually been measured by a photomultiplier tube (PMT). However, the method requires a precise alignment to achieve critical phase matching in the nonlinear crystal, and it is expensive. Recently, an alternative technique which uses the two-photon absorption (TPA) of a semiconductor device as a nonlinear process has been developed. It replaces the SHG crystal and PMT with semiconductor devices such as photodiode, light emitting diode, laser diode, etc.. In this technique, the pulses from the Michelson interferometer are directly focus ed onto the semiconductor devices, and TPA in a semiconductor device directly generates photocurrents in the device itself. The detection of photocurrents as a function of time delay yields autocorrelation signals.

The autocorrelator based on semiconductor devices has several advantages over the conventional autocorrelator with SHG crystal and PMT. The semiconductor device is inexpensive, compact, robust and polarization independent, and gives non-phase-matched detection for a broad photon energy range from one-half band-gap to full band-gap.

In principle, the two-photon response of the autocorrelators is proportional to the product of the peak power and average power of incident light, under the irradiation of a mode-locked pulse train [1]. Thus the autocorrelator sensitivity is often defined as the product of the peak power and average power of the minimum detectable signal. For commercial instruments using SHG and PMT, it is usually $(P_{pk}P_{av}) \sim 1-10\ (mW)^2$.

Since the first report on TPA autocorrelators in 1992 [2], various TPA autocorrelators have been experimentally demonstrated and the available wavelength ranges cover from 0.5 $\mu$m to 3.7 $\mu$m. The best sensitivity achieved by these autocorrelators was $(P_{pk}P_{av}) \sim 0.08\ (mW)^2$ by combining an InGaAsP waveguide and lock-in detection, which is about two orders of magnitude better than that of the conventional autocorrelator [3]. The review on TPA autocorelators was presented in Ref.4. In a visible wavelength Feurer et. al. [5] obtained the intensity autocorrelation signal for the femtosecond pulses from a dye laser system which was operated at center wavelength of 497 nm using a SiC photodiode. They demonstrated the feasibility of an autocorrelator based on the SiC photodiode. But their autocorrelation signal fluctuated a little due to shot-by-shot measurement which might be caused by low repetition rate of the dye laser(1 Hz) and high pulse energy which was up to 250 $\mu$J, relatively higher than that of a pulse from a typical femtosecond laser oscillator ($\sim$ nJ). Thus it is not quite certain whether a SiC photodiode introduces extra error and whether it is operable at other wavelength and powers.

In this paper we report the extended utility of the SiC photodiode for the autocorrelation measurement. The autocorrelation signals of not merely the femtosecond pulses but even the picosecond pulses from a widely used Rh6G dye laser were successfully measured in real time by using an autocorrelator based on two-photon absorption in a SiC photodiode at near 600 nm wavelength. We also present the sensitivity of the autocorrelator, and compare the results with that obtained by SHG crystal and PMT.

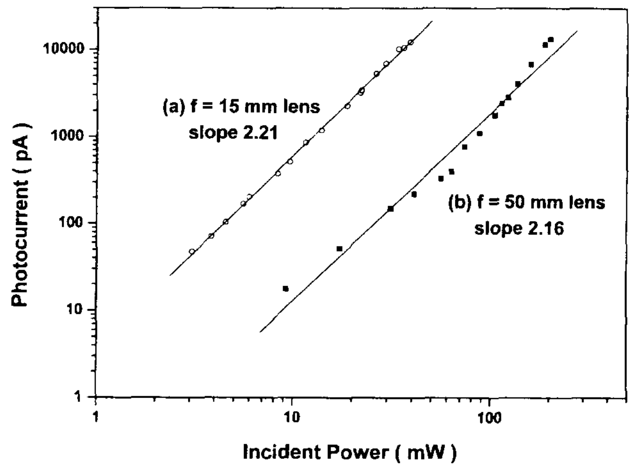


FIG. 1. Two-photon induced response of the SiC photodiode as a function of input power for 76 MHz, 8 ps pulse train generated from mode locked Rh6G dye laser with center wavelength of 577 nm. The pulse was focused by using a microscope objective with apparent focal length of 15 mm (a), and plano-convex lens with focal length of 50 mm (b). The straight lines represent quadratic fitting.

## II. MEASUREMENT OF PHOTOCURRENT INDUCED BY TWO-PHOTON ABSORPTION IN A SIC PHOTODIODE

### II. A. Power dependence of photocurrent

In order to examine whether the photocurrent was due to two-photon response, we measured the power dependence of the average photocurrent in the SiC photodiode under irradiation of the light from the Rh6G dye laser system. The Rh6G dye laser was pumped by frequency-doubled mode-locked Nd:YAG laser with 76 MHz repetition rate. When the Rh6G dye laser was synchronously mode-locked by matching precisely the cavity length of the dye laser with that of the pump laser, the pulse width was about 8 ps and the center wavelength was about 577 nm. The SiC photodiode (Laser Component JEC1) has a peak response at 270 nm wavelength and a linear spectral bandwidth from 210 nm to 380 nm, which means a two-photon response in the region of 420 - 780 nm [6]. We also used a low noise current preamplifier(EG&G 5182) which had a bandwidth 10 kHz with the maximum sensitivity $10^8$ V/A for producing a voltage output proportional to the generated photocurrent.

The laser beam was attenuated by a variable neutral density filter and then illuminated the SiC photodiode.

In a preliminary experiment using unfocused light with average power of 200 mW, we were able to measure only negligible photocurrent when the laser was operated in nearly continuous-wave mode by mismatching the cavity length. We observed a detectable photocurrent of about 50 pA, i.e. 5 mV output voltage through the input impedance of 1 M$\Omega$ in the oscilloscope and the gain of $10^8$ V/A in the preamplifier when the laser was operated in synchronously mode-locked mode.

Figure 1 shows the power dependence of photocurrents in the SiC photodiode on which the incident light was focused by a microscope objective with apparent focal length of 15 mm (a) and a plano-convex lens with focal length of 50 mm (b), respectively. The saturation effect was not found within the input power range shown in Fig. 1. No optical damage was found after repetitive irradiation during the whole measurement. The slope of the straight lines in the double-logarithmic plot represent nearly quadratic response for a substantial range of incident powers, indicating that the response is due to a second-order process, i.e. two-photon induced conductivity. From these data, we estimate that the sensitivity of our autocorrelator using a microscope objective is $(P_{pk}P_{av}) \sim 4 \times 10^3\ (mW)^2$. This sensitivity is inferior by three orders of magnitude to that of a commercial autocorrelator based on second harmonic crystal and PMT. Nevertheless this sensitivity is sufficient for measuring the pulse width of picosecond pulses from our dye laser of which the average power is as small as 10 mW. It may be possible to further improve the sensitivity of the autocorrelator by increasing the preamplifier sensitivity and focusing the light more tightly onto the surface of the photodiode. Despite the lower sensitivity, usage of a SiC photodiode provides considerable convenience and

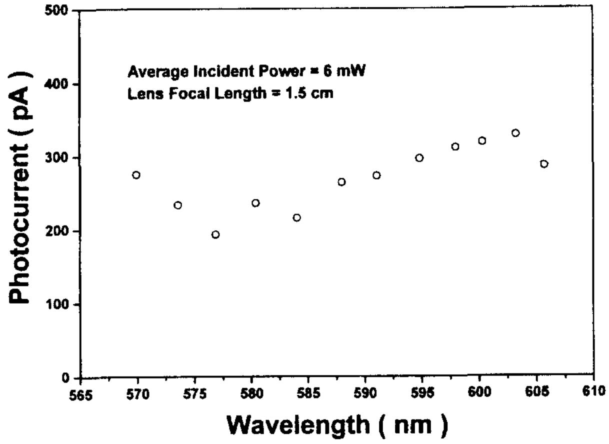


FIG. 2. Spectral dependence of two-photon induced photocurrent in the SiC photodiode measured with an 76 MHz train of 8 ps pulses. The average power was 6 mW.

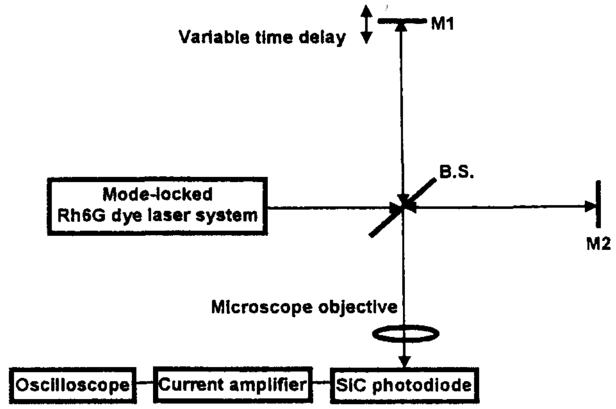


FIG. 3. Experimental setup for two-photon autocorrelator. M1, M2 were total mirrors and B. S. was a 50:50 beam splitter. The variable delay was achieved by a loud speaker or rotating mirror pair.

simplicity in the actual measurement process from the advantages mentioned above. In the case of using a SHG crystal and a PMT, a cut-off filter is necessary to separate the second harmonic from the fundamental before the second harmonic wave is incident on the PMT, and the light in the laboratory must be turned off to exclude the background noise and prevent damage to the PMT due to the unwanted light. But in the case of using the SiC photodiode there is no need for a cut-off filter or for darkness. Indeed, we observed no detectable photocurrent in the SiC photodiode under normal light.

### II. B. Spectral dependence of photocurrent

Figure 2 shows the wavelength dependence of two-photon response of the SiC photodiode. We used a quartz birefringent plate to vary the center wavelength of the Rh6G dye laser from 570 nm to 605 nm. The incident average power was adjusted to 6 mW by using a variable neutral density filter and the pulse width was about 8 ps. The laser beam was focused onto the photodiode by the microscope objective. The incident average power and pulse width had some fluctuation during the experiments. As shown in Fig. 2 no significant change of the two-photon response was observed, which was expected due to the broad bandwidth of two-photon response of a SiC photodiode. It should be noticed that the narrow wavelength tuning range in Fig. 2 was due to the limit of the bandwidth of a birefringent plate and a Rh6G dye laser. It is expected that the range of two photon response of the SiC photodiode can reach the whole wavelength tuning range of almost all sort of dyes except for the two extremes near 400 nm ultraviolet and near 800 nm infrared.

## III. TWO-PHOTON ABSORPTION AUTOCORRELATION FOR THE PULSES FROM THE MODE-LOCKED RH6G DYE LASER.

Experimental setup for the two-photon absorption autocorrelator is sketched in Fig. 3. This is the same as the conventional autocorrelator based on SHG and PMT, except that the photodiode has replaced the SHG crystal and PMT. The incident pulse was split into two replicas by a beam splitter and proceeds to reflecting mirror M1, M2. The reflected pulses from M1 and M2 overlapped at the beam splitter with relative time delay. The overlapped pulses focused onto the surface of the SiC photodiode through the microscope objective.

Figure 4 shows the intensity autocorrelation signals of picosecond pulses of the Rh6G dye laser from a con-

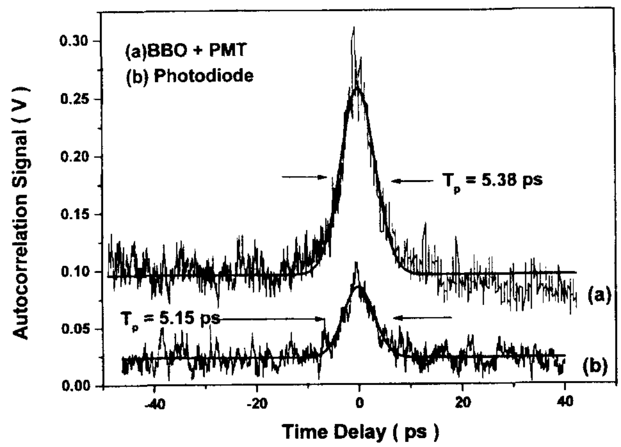


FIG. 4. Intensity autocorrelation signal of 5 ps pulses : (a) with the 100 $\mu$m BBO crystal and PMT, and (b) with the SiC photodiode.

ventional autocorrelator based on a beta barium borate (BBO) crystal of 100 $\mu$m thickness and PMT (a), and the SiC photodiode (b). In both cases the time delay was achieved by a rotating mirror pair located at one arm of a Michelson interferometer [7]. If Gaussian pulse shape was assumed, there was a good agreement between the measured pulse widths, in which the pulse width was 5.38 ps with the BBO crystal and the PMT and 5.15 ps with the SiC photodiode, respectively. In this experiment we reduced the pulse width by careful alignment of the laser cavity. The autocorrelation measured with the SiC photodiode is noisier than that obtained with the BBO crystal and the PMT, due to the fact that the sensitivity of the autocorrelator witthe SiC photodiode is not so good as that of the BBO crystal and the PMT. The narrow spikes in the middle of the autocorrelation traces represent incomplete mode-locking of picosecond pulses, which is a typical characteristic of synchronously mode-locked dye lasers. The contrast ratio of the background and the correlation peak depends on the state of mode-locking and the overlap of the two replicas of pulses [8]. The contrast ratio of the autocorrelation signal obtained using the BBO crystal and the PMT was nearly 1:3 as shown in Fig. 4(a). But that obtained using the SiC photodiode was about 1:4, which might have resulted from incomplete overlap between two replicas. It should be noticed that the output voltage of the current preamplifier on an AC coupled-mode appeared to be zero when only one replica of the pulses was incident on a SiC photodiode. The contrast ratio should be 1:5 if pulses were completely mode-locked and the two replicas exactly overlapped.

We also measured an autocorrelation signal of femtosecond pulses from a hybridly mode-locked Rh6G dye laser with the 3,3'-diethyloxadicarbocyanine iodide (DODCI) saturable absorber. The center wavelength was 620 nm. Figure 5 shows the intensity autocorrelation (a) and the interferometric autocorrelation (b) using the SiC photodiode. In these cases the time delay was achieved by a loud speaker. If the sech$^2$ pulse shape was assumed, the pulse width from the intensity autorrelation trace was fitted to 103 fs. The contrast ratio in the interferometric autocorrelation is nearly 1:8, which is consistent with the expectation, but the pulse was largely chirped due to improper control of the group velocity dispersion over intra- and/or extra-cavity, as shown in Fig. 5(b) [9].

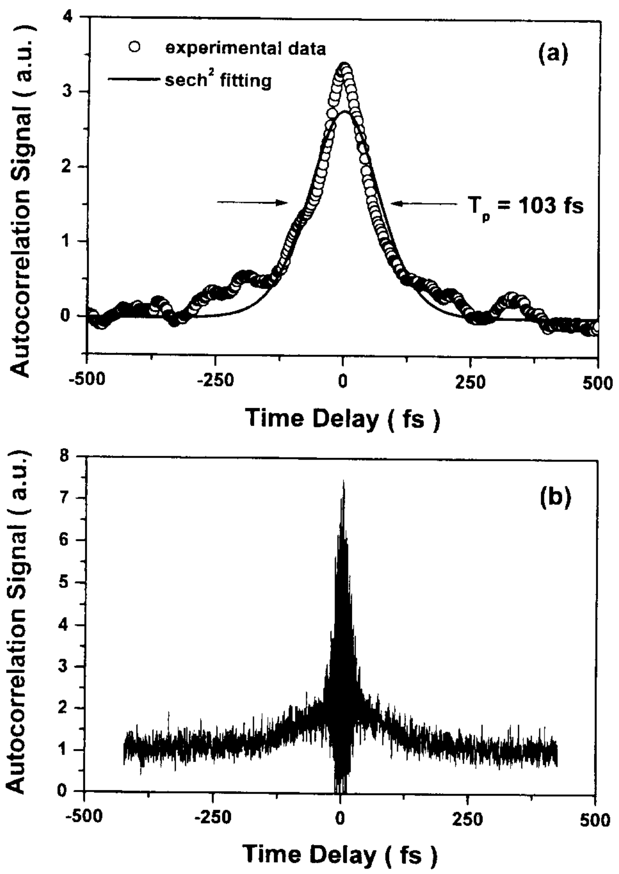


FIG. 5. Intensity (a) and interferometric (b) autocorrelation measurements of femtosecond pulses from hybridly mode-locked Rh6G dye laser with the SiC photodiode.

## IV. CONCLUSION

We have characterized the power dependence and spectral dependence of two-photon absorption in the SiC photodiode, and we successfully applied it to obtaining the autocorrelation traces of picosecond and femtosecond pulses from a Rh6G dye laser. The autocorrelation trace using a SiC photodiode was in good agreement with the results of a conventional autocorrelator using a BBO and a PMT. We confirm that a SiC photodiode is very suitable for a nonlinear device for measuring the pulsewidth of ultrashort pulses in a visible wavelength. The sensitivity of the autocorrelator with SiC photodiode was $4 \times 10^3$ $(mW)^2$, permitting the autocorrelation trace measurement of pulses with 8 ps pulsewidth, but only 10 mW average power. Further improvement of the sensitivity of the autocorrelator can be achieved by more efficient amplification of induced photocurrent or tighter focusing of light on the surface of the photodiode.

## ACKNOWLEDGMENTS

This research was supported by a grant from the Korea Science and Engineering Foundation (97-0702-03-01-3) and the Basic Science Research Institute Progra m of the Korea Ministry of Education (BSRI-97-2421).

## REFERENCES

[1] F.R. Laughton, J.H. Marsh, D.A. Barrow and E.L. Portnoi, IEEE J. Quantum Electron. **QE-30**, 838 (1994).
[2] Y. Takagi, T. Kobayashi, K. Yoshihara and S. Imamura, Opt. Lett. **17**, 658 (1992).
[3] H.K. Tsang, L.Y. Chan, J.B.D. Soole, H.P. LeBlanc, M.A. Koza and R. Bhat, Elec. Lett. **31**, 1773 (1995).
[4] D.T. Reid, W. Sibbett, J.M. Dudley, L.P. Barry, B. Thomsen and J.D. Harvey, Optics and Photonics News **9**, No 5, 50 (1998).
[5] T. Feurer, A. Glass and R. Sauerbrey, Appl. Phys. B **65**, 295 (1997).
[6] D.M. Brown, E.T. Downey, M. Ghezzo, J.W. Kretchmer, R.J. Saia, Y.S. Liu, J.A. Edmond, G. Gati, J.M. Pimbley and W.E. Schneider, IEEE Transaction on Electron Devices **40**, 325 (1993).
[7] Z.A. Yasand N.M. Amer, Optics Comm. **36**, 406 (1981).
[8] H.P. Weber and H.G. Danielmeyer, Phys. Rev. A **2**, 2074 (1970).
[9] J.-C. M. Diels, J.J. Fontaine, I.C. McMichael and F. Simoni, Appl. Opt. **24**, 1270 (1985).