Development of a charge-carrier drift velocity measurement system in diamonds by using a UV pulse laser

F. Fujita[1], A. Homma[1], Y. Oshiki[1], J.H. Kaneko[1], K. Tsuji[1], K. Meguro[2],

Y. Yamamoto[2], T. Imai[2], T. Teraji[3], T. Sawamura[1] and M. Furusaka[1]

Hokkaido University[1], Sumitomo Electric Industries Ltd[2], Osaka University[3]

There are continuing efforts of developing faster FETs and diamond is one of the strong candidates as a base semiconductor. Since the upper-limit-frequency of diamond FETs determines saturated drift-velocities of charge-carriers, we need to first characterize diamond to develop better FETs. It is, however, not easy to measure the velocities with response time of less than 20 ns. Therefore, we developed a drift velocity measurement system using a time-of-flight (TOF) technique with a UV laser with 100 ps pulse-width. In order to realize response times faster than 20 ns, we employed a 50 ohm coaxial cable as a load, with which we could effectively reduce the stray capacitance and inductance, and also, suppress reflections in the signal which gives false signals. As a result, we can measure carrier-transit times shorter than 10 ns.

Keywords: time of flight, UV pulse laser, carrier drift velocity, CVD diamond

I. Introduction

The use of diamond as high frequency field-effect transistors (FETs) can be expected to be advantageous because diamond has high carrier-mobilities, thermal conductivities and also high breakdown field strength. The surface channel FETs and p-i-p high frequency FETs have been developed, and the saturated drift velocities in the i-layer of diamond FETs determine the upper limits of its performance. Charge-carrier mobilities in diamond can be determined by measuring the drift velocities with respect to external electric-field strengths. One of the drift velocity measurement methods is the time-of-flight (TOF) technique.

The TOF technique has been well established as a mobility measurement method for minority carriers in semiconductors [1-5]. To create pulsed electron-hole pairs to initiate the TOF measurement, we could use the electric injection or visible light irradiation method, since the energy gap between valence bands and conduction bands is about 1 eV for intrinsic silicon and 0.025 eV for doped silicon. In contrast to it, the energy gap of intrinsic diamond is known to be 5.49 eV, and injection quanta must have energies greater than 5.49 eV to create electron-hole pairs. Alpha particles of 5.846 MeV from ^{241}Am have frequently been used as injection quanta [6]. In such cases, the rise times of the signal (the transit times) and the total-charge are normally measured a charge-sensitive preamplifier [7,8]. However, the minimum response-time of the charge sensitive preamplifier is normally 10~20 ns, therefore it is difficult to measure charge-carrier transit times shorter than 10 ns [8,9]. Moritz *et al.* [10] have developed a broadband preamplifier aimed mainly at high counting rate capability, but there was no description on output linearity.

If we could eliminate the preamplifier in the system, which limits the response times, we would be able to construct a better system. It is possible to realize such thing by making injection quantum flux intense. Canali, *et al.* [11,12] used an accelerated electron beam and Pan, *et al.* [13] used soft X-rays from a synchrotron as the injection quanta. Ultra violet (UV) pulsed laser light has also been used to measure charge-carrier mobilities in diamond [14-16]. Use of a high power UV laser with a pulse width shorter than 1 ns can make easy to measure carrier transit times shorter than 10 ns.

This investigation reports the development of a charge-carrier drift velocity measurement system without a preamplifier (a TOF measurement system), which can measure transit times shorter than 10 ns. The system used the fifth higher harmonic of a Nd:YAG laser light with 100 ps pulse width and UV energies of 6 mJ per pulse (a wavelength of 213 nm: photon energy of 5.807 eV). The reliability of this system was confirmed by diamond samples where the charge-carriers transport properties had been evaluated by α particles [8,9].

II. Experimental Setup

Special cares must be taken to set up the TOF measuring apparatus when using a UV short-pulsed laser of 100-picosecond order: the way of bias-voltage supply and the signal detection. In the latter case, reflections of a signal pulse at the connectors and existence of stray capacitance and inductance in the system have to be taken care of.

Figure 1 shows a schematic diagram of the developed TOF system. The DC bias voltage was applied between semi-transparent electrodes evaporated on the front and back surfaces of the diamond samples. UV pulsed laser light passed through the front electrode was absorbed in the diamond within about 3 μm of the surface. When the charge-carriers are created by the UV photons, a mirror charge is induced in the electrodes spontaneously. The current continues to flow until the created electrons and holes reach the electrodes and the current vanish when the carriers combine with the mirror charges. Ideally, the current is constant during the charge-transit period and drop-off rapidly when they reach the electrodes. The current from the back-surface electrode to the GND was transformed to a voltage signal by the impedance of the coaxial cable. The signals were recorded with a 1 GS/s digital oscilloscope using a 50-Ω terminator. A resistor is often placed between an electrode and ground, and an oscilloscope measures a voltage drop signal across the resistor. However, for very short pulse signals, a resistor does not work as a pure resistive-component but also capacitive and inductive characters set in, and its response property is deteriorated. Our measurement system used the characteristic impedance of a coaxial cable as a load, therefore, the response property was determined solely by the frequency characteristics of the coaxial cable, resulted in the very fast response.

Table 1 details the characteristics of the diamonds used in this study. Sample #1 is an optical grade type IIa diamond synthesized at high pressure and high temperature (HP/HT). Samples #2 and #3 were fabricated by a plasma assisted chemical vapor deposition (PCVD) technique.

III. Results and Discussion

Figure 2 shows typical TOF signals measured at +40, +80 and +140 V of bias voltages in sample #1. It is likely that the sharp peaks at t=0 are caused by the photoelectric effect of the UV laser light that irradiated the front-electrodes. From the results of the reference measurements by using α particles, it was confirmed that there was a large difference in their behavior between electrons and holes. Electrons have a tendency of trapped in short distances. In contrast to it, holes, although they also trapped, because the sites have rather shallow trapping levels, are re-emitted by thermal excitations, most of them can reach the electrode. The results of the sample #1 showed the behavior described above, in which plateau signals reflect the movement of holes and the signals decreased corresponding to the holes reached at the electrode around 2 μs. The charge transit time in an ideal-diamond crystal of 0.3 mm thickness is normally about several ns, but in this case, the sample has the transit time of a few μs. It is attributed to the hole trapping and re-emission phenomena that is explained above [9]. Figure 3 shows the results of measurements by our system in the sample #2 that had been evaluated by α particles. It was found that electron and hole currents flowed simultaneously. The transit time of holes was estimated to be about 70 ns. Figure 4 shows the result of measurements for the sample #3 that could not have been evaluated by measurements using α particles due to the 20 ns limitation. The developed TOF system, however, enabled us to measure shorter transit times and gave the result of about 6 ns of transit time for the sample #3. These results were agreed quantitatively with those of measurements using α particles and we confirmed that the system could correctly detect the signal produced by the charge in the diamond.

A faster digital oscilloscope is required to measure shorter transit times. To reduce the sharp peaks at t=0, it is necessary to remove the metal layer on the portion of the diamond surfaces where the laser beam is irradiated or to adopt comb-shaped electrodes. Saturated drift velocities can be measured by applying high voltage to a sample. To avoid electric discharges, the sample must be in a vacuum or a pulsed bias voltage must be applied. The system presented here has the capability to be used in measurements of the transit time at short carrier travel distances and it will be able to evaluate the fast dynamics of the charge-carriers in diamond.

Acknowledgement

This work was performed within the frame of the Advanced Diamond Device Technology Project. Also a part of this work was supported by KAKENHI(15360498).

References

[1] J.R. Haynes and W. Shockley: Phys. Rev. **51** (1951) 835.

[2] J.P. McKelvey: J. Appl. Phys. **27** (1956) 341.

[3] A. Sconza and G. Torzo: Eur. J. Phys. **8** (1987) 34.

[4] A. Sconza, G. Galet and G. Torzo: Am. J. Phys. **68** (2000) 80.

[5] S.M. Sze; *Semiconductor Devices*, 2nd Ed., John Wiley (2002).

[6] F. Nava, C. Canali, M. Artuso, E. Gatti, and P.F. Manfredi: IEEE **NS-26** (1979) 308.

[7] J. Kaneko and M. Katagiri: Nucl. Instrum. Meth. A 383 (1996) 547.

[8] Y. Oshiki, J.H. Kaneko, K. Hayashi, K. Megro, F. Fujita, A. Homma, *et al.*: ICNDST-10 (2005) P6-25.

[9] J.H. Kaneko, T. Tanaka, Y. Tsanimura, A. Birumati, Y. Hirai, M. Katagiri, Y. Ikeda, T. Nishitani, T. Iida, and T. Sawamura: New Diamond and Frontier Carbon Technology **14** (2004) 299.

[10] P. Moritz, E. Berdermann, K. Blasche, H. Stelzer and B. Boss: Diamond and Related Materials **10** (2001) 1765.

[11] A.A. Quaranta, C. Canali and G. Ottaviant: Rev. Sci. Instrum. **41** (1979) 1205.

[12] C. Canali, E. Gatti, S.F. Kozlov, P.F. Manfredi, C. Manfredotti, F. Nava, and A. Quirini: Nucl. Instrum. Meth. **160** (1979) 73.

[13] L.S. Pan, S. Han, D.R. Kania, K.K. Gan, S. Zhao, *et al.*: Mat. Res. Soc. Symp. Proc. **302** (1993) 245.

[14] C.E. Nebel, J. Muenz, M. Stutzmann, R. Zachai, and H. Guetter: Phys. Rev. **B55** (1997) 9786.

[15] E. Lefeuvre, J. Achard, M.C. Castex, H. Schneider, C. Beille, and A. Tardieu: Diamond and Related Materials **12** (2003) 642.

[16] J. Isberg, J. Hammersberg, E. Johansson, T. Wikstroem, D.J. Twichen, et al.: Science **297** (2002) 1670.

[17] J.H. Kaneko, T. Teraji, Y. Hirai, M. Shiraishi, S. Kawamura, S. Yoshizaki, T. Ito, K. Ochiai, T. Nishitani and T. Sawamura: Rev. Sci. Instrum **75** (2004) 3581.

Tables

Table 1. Diamonds used in this study

Sample ID	Crystal Type	Size [mm^3]	Contacts
#1*	HP/HT , type IIa single crystal	4×4×0.3	Pt/Pt
#2**	Plasma CVD, single crystal [17]	4×4×0.3	Al-Ti/Au
#3*	Plasma CVD, single crystal	4×4×0.3	Al/Al

Fabricant: *Sumitomo Electric Industry Ltd., **Osaka University

Figure Captions

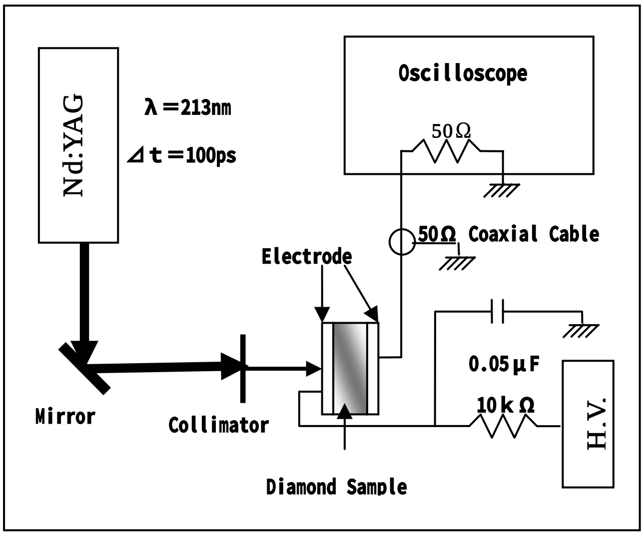
Figure 1. Time-Of-Flight setup. A Nd:YAG laser with the fifth higher harmonic was used as the light source. The sample is biased by a DC voltage source. Signals were recorded by a fast digital oscilloscope.

Figure 2. TOF signals measured in sample #1. Three different DC bias values were applied.

Figure 3. TOF signal at +120 V_{DC} bias voltage of sample #2.

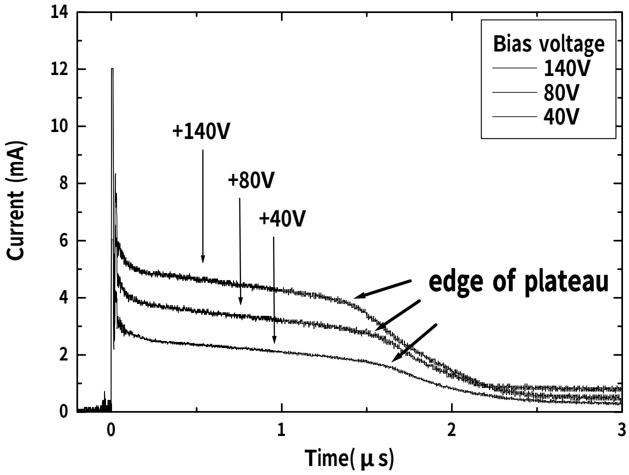
Figure 4. TOF signal at +120 V_{DC} bias voltage of sample #3.

Fig. 1



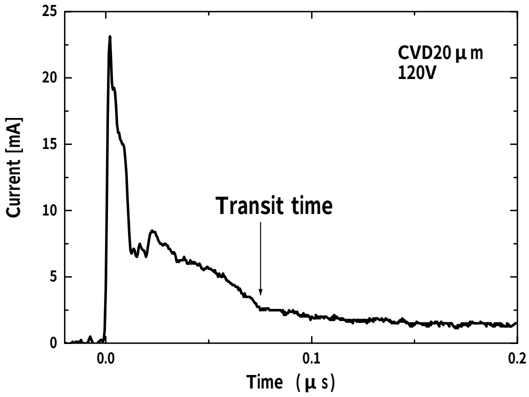
Nd:YAG
λ＝213nm
⊿t＝100ps
Oscilloscope
50Ω
50Ω Coaxial Cable
Electrode
0.05μF
10kΩ
H.V.
Mirror
Collimator
Diamond Sample

Fig. 2



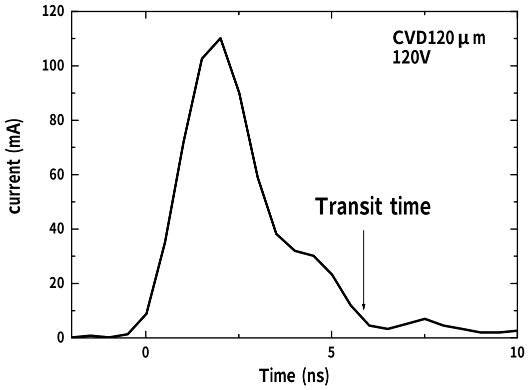
Bias voltage
140V
80V
40V
+140V
+80V
+40V
edge of plateau
Current (mA)
Time(μs)
0
2
4
6
8
10
12
14
0
1
2
3

Fig. 3



CVD20 μm
120V
Transit time
Current [mA]
Time (μs)
25
20
15
10
5
0
0.0
0.1
0.2

Fig. 4



CVD120 μm
120V
Transit time
current (mA)
Time (ns)
120
100
80
60
40
20
0
0
5
10