High Power Terahertz Induced Carrier Multiplication in Silicon

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***Abstract*—The application of an intense THz field results a nonlinear transmission in high resistivity silicon. Upon increasing field strength, the transmission falls from 70% to 62% due to carrier generation through THz-induced impact ionization and subsequent absorption of the THz field by free electrons.**

I. INTRODUCTION

RECENTLY we reported THz induced nonlinear carrier generation in high resistivity silicon through impact ionization [1]. The THz field energizes conduction band electrons which impact bound electrons in the valence band. If the conduction band electron gains sufficient kinetic energy, the impact event lifts the bound electron into the conduction band generating a new electron-hole pair. The process continues in cascaded manner in the time span of the THz transient, thus generating a large number of free carriers.

THz field induced impact ionization is also reported for GaAs and InSb [2, 3] which are direct bandgap semiconductors. Silicon, which is an indirect semiconductor, requires stronger field strength to initiate significant impact ionization on a subpicosecond time scale. Previously we used an antenna array to enhance the field strength of THZ pulses from lithium niobate to several MV/cm. In that case the impact ionization is limited only to small region of the substrate near the antenna tips where field enhancement is largest. It is therefore difficult to observe a change in overall transmission amplitude between high and low THz fields, and quantitative spectroscopy investigation of the effect is challenging. Here we report on strong transmission modulation through bare, intrinsic silicon by application of a THz field of several MV/cm generated from an organic crystal (DSTMS, pumped with femtosecond pulses at 1300 nm).

II. RESULTS

When high resistivity silicon with an array of metal antennas for field enhancement is illuminated with $LiNbO_3$-based source covering frequencies from 0.4 to 1.4 THz, and with peak field strength of about 265 kV/cm, impact ionization in the silicon near the antenna tips leads to the generation of carriers which in turn change the local dielectric properties of the substrate. This results in a significant redshift of the resonance frequency of the antenna array, as shown in Fig. 1.

THz generation from DSTMS covering frequencies from 1 to 5 THz, enables us to access several MV/cm electric field strength. This field strength is sufficient for impact ionization to occur without additional local field enhancement which makes it easier to probe the carrier scattering dynamics. A single –pulse THz transmission measurement shows a decrease transmission through the silicon wafer as the incident field strength is increased as shown in fig. 2. At low field the amplitude transmission is about 70%, as expected for undoped silicon due to Fresnel losses. As the field strength increases, the transmission decreases to about 62%. The decrease in transmission is due to absorption of THz field by free carriers generated by THz induced impact ionization with saturation at field strengths of above 80% of the highest field strength available. This decrease in transmission is due to absorption of the THz field by free carriers generated by THz-induced impact ionization. We tentatively attribute the saturation of the nonlinear transmission to a combination of saturation of conduction band electronic states and an increase of the effective mass at high momentum states at high THz fields [4].

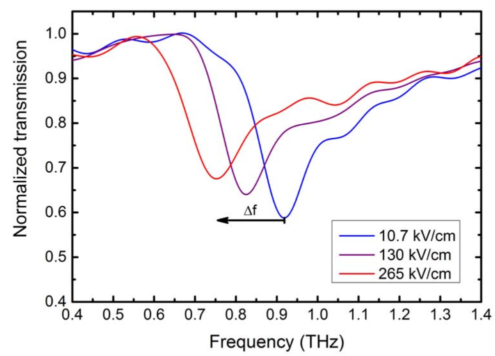

Fig. 1. Normalized THz transmission of a gold antenna array on a high resistivity silicon substrate as a function of frequency for different incident THz peak field strengths. The antenna is designed to have a linear resonance frequency of 0.9 THz.

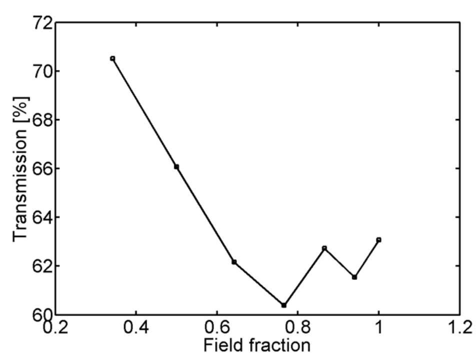

Fig. 2. Amplitude transmission through silicon as a function of electric field strength.

REFERENCES

[1]. A.T. Tarekegne, K. Iwaszczuk, and M. Zalkovskij, A.C. Strikwerda, and P.U. Jepsen "Impact ionization in high resistivity silicon induced by an intense terahertz field enhanced by an antenna array," *New J. Phys.* (accepted, 2015).

[2]. H. Hiroi, K. Shinokita, M. shirai, S. Tani, Y. Kadoya, and K. Tanaka, "Extraordinary carrier multiplication gated by a picosecond electric pulse," *Nat. Comm.*, 2, 594, 2011.

[3]. M. Hoffmann, J. Hebling, H. Hwang, K.L., Yeh, and K. Nelson, "Impact ionization in InSb probed by terahertz pump—terahertz probe spectroscopy," *Phys. Rev. B* 79, vol. 161201, 2009.

[4]. M. Hoffmann, and D. Turchinovich, "Semiconductor saturable absorbers for ultrafast terahertz signals," *App. Phys. Lett. 96*, 151110, 2010.