Photoconductive Step-Function Sampling

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***Abstract*—Measurement of picosecond electrical signals using a photoconductive step-function gate is demonstrated analytically and experimentally. The time resolution of our step-function technique is limited only by the rise time of the step-function, which is approximately the same as the laser pulse width. Also, a regular, undoped semiconductor material, which is essential for the realization of a short-duration gate, can be used instead of the highly defected material. The use of undoped material gives 10 to 100 times higher sensitivity in the measurement than the impulse-function technique because of the high mobility of the undoped material.**

I. Introduction

SAMPLING TECHNIQUES are the best methods for measuring very fast varying electrical signals. One of the fastest sampling methods is the electro-optic sampling (EOS) technique utilizing the Pockels' effect of a birefringent electro-optic crystal [1]. However, the measurement sensitivity of the EOS technique is low due to the small change of the index of refraction with the electric field change. Better measurement sensitivity is obtainable using another sampling method known as the photoconductive sampling (PCS) technique [2]. This technique uses a very-short-duration optoelectronic gate to map out fast electrical transients. The gate, which consists of a photoconductive gap, is usually fabricated on semiconductor materials. The photoconductive response of the material determines the sensitivity and the temporal response of the measurement. The temporal response, i.e. the measurement bandwidth, is limited because the sampled waveform is the cross-correlation of the real electrical signal waveform and the response function of the gate. Therefore, the shorter the gate response, the more accurately the electrical signal can be measured. A short gate response has been achieved with the fabrication of photoconductive gaps on materials having a subpicosecond life time of photogenerated carriers. Typical materials used are ion-damaged silicon-on-sapphire [3] and low-temperature-grown GaAs [4]. The short-carrier-life time has been attained using defects in the materials. The defects reduce the mobility of carriers, resulting in the decrease of the measurement sensitivity, although the decreased sensitivity is still higher than that of the EOS technique.

In this letter, we introduce a new photoconductive sampling technique utilizing a step-function gate that avoids the need to sacrifice sensitivity by introducing defects in the gate material. Also, the measurement bandwidth of our new technique is not limited by the gate duration, which is mostly dominated by the carrier lifetime for conventional photoconductive gates. The bandwidth of our technique is determined only by the pulse width of the laser that we use for driving the photoconductive step-function gate, which will be described.

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II. Impulse Photoconductive Sampling

A conventional PCS technique using a short-duration gate will be discussed briefly here before explaining our new scheme.

Suppose $f(t)$ is the voltage signal to be sampled and $h(t)$ is the response function of the sampling gate. These two functions are assumed to be perfectly synchronized. In general, the measured signal $F(t)$ is the cross-correlation between $f(t)$ and $h(t)$:

$$F(t) = \int_{-\infty}^{\infty} f(t')h(t'-t)dt'. \quad (1)$$

For a rectangular gate-function, $h(t)$, given by

$$h(t) = \begin{cases} h_0, & \text{for } 0 \le t \le \tau \\ 0\ , & \text{otherwise,} \end{cases} \quad (2)$$

the signal $F(t)$ becomes

$$F(t) = h_0 \int_{t}^{t+\tau} f(t')dt'. \quad (3)$$

If the gate duration t is small enough compared to the signal under study, $f(t)$, the signal that we measure, $F(t)$, is given by

$$F(t) \simeq h_0 \tau f(t) \quad (4)$$

and $F(t)$ is proportional to the signal under study $f(t)$. What this last equation tells us is that in order to have large $F(t)$, it is necessary to have a large h_0 while maintaining the large τ. Here h_0 is the sensitivity of the photoconductive-gate response and is proportional to the mobility of the material, which is very material dependent. Also, h_0 is usually in a trade-off relationship with the gate recovery-time τ. Therefore, it is almost impossible to get high sensitivity with picosecond time-resolution in a conventional photoconductive sampling technique. The technique we are proposing next, however, can have very high measurement sensitivity without sacrificing the measurement time-resolution.

III. Step-Function Photoconductive Sampling

We are proposing not to sample with a short photoconductive gate but, on the contrary, with a step-function gate. We will show that the step-function sampler can give very large sensitivity h_0 and adjustable gate-duration τ.

Suppose we sample the signal $f(t)$ with a step-function $h'(t)$ given by

$$h'(t) = \begin{cases} h'_0, & \text{for } t \geq 0 \\ 0\ , & \text{for } t < 0. \end{cases} \quad (5)$$

Then, the measured signal $F(t)$ becomes

$$F(t) = h'_0 \int_t^{\infty} f(t')dt'. \quad (6)$$

This equation can also be expressed as

$$F(t) = h'_0 \int_{-\infty}^{\infty} f(t')dt' - h'_0 \int_{-\infty}^{t} f(t')dt'$$

$$= C - h'_0 \int_{-\infty}^{t} f(t')dt', \quad (7)$$

where C is a constant. From this equation, we know that the cross-correlation of the signal under study with a step-function is proportional to the signal integral. The signal under study can be recovered from $F(t)$ using mathematical differentiation as follows:

$$F(t) - F(t+\tau) = -h'_0 \int_{-\infty}^{t} f(t')dt' + h'_0 \int_{-\infty}^{t+\tau} f(t')dt'$$

$$= h'_0 \int_{t}^{t+\tau} f(t')dt'. \quad (8)$$

For a small τ, which we can arbitrarily introduce,

$$F(t) - F(t+\tau) \simeq h'_0 \tau f(t). \quad (9)$$

With (9), we have shown that the signal under study is recoverable using a step-function gate.

IV. Sampling Using a Quasi-Step-Function

It is indeed very difficult to produce a perfect step function. What can be obtained, however, is a sampling function with a fast risetime limited by the laser pulse and with a long decay of 10–100 times the duration of the signal under test. When the quasi-step-function $h(t)$ is used for the gate function, the signal recovered from the measurement is given by

$$F(t) - F(t+\tau) = \int_{-\infty}^{\infty} f(t')h(t'-t)dt'$$

$$- \int_{-\infty}^{\infty} f(t')h(t'+\tau-t)dt'. \quad (10)$$

For the slow-varying $f(t)$ and small τ, the above expression becomes

$$F(t) - F(t+\tau) = \int_{-\infty}^{\infty} f(t')h(t'-t)dt'$$

$$- \int_{-\infty}^{\infty} f(t')\{h(t'-t) - \tau \frac{dh(t'-t)}{dt}dt'$$

$$= \tau \int_{-\infty}^{\infty} f(t') \frac{dh(t'-t)}{dt} dt'. \quad (11)$$

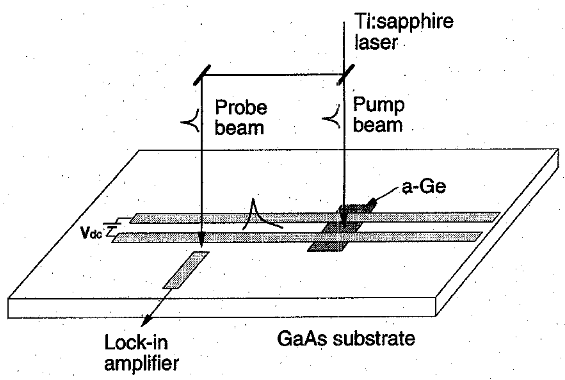

Fig. 1. Diagram of the experimental scheme. A picosecond electrical pulse is generated between the lines of the coplanar strip in a region that is doped with amorphous Ge. The electrical transient is sampled by the step-function gate fabricated on an undoped GaAs layer. The gate is 1.0 mm away from the generation point.

Note that the difference $F(t) - F(t+\tau)$ is equal to the cross-correlation between the signal and the time derivative of the quasi-step-function. The equivalent sampling function $dh(t'-t)/dt$ has a duration as short as the rise time of the quasi-step-function $h(t)$ that is very short in the case of photoconductive sampling. The rise time is mostly determined by the laser pulse width, which can be shorter than 100 fs.

From (11), we know that the photoconductive step-function sampling has the following advantages over the conventional impulse sampling:

1) It has an ultimate temporal resolution limited only by the laser pulse width. The resolution can be as short as 100 fs because it is determined by the risetime of the sampling step-function and the risetime is almost the same as the laser pulse width. On the other hand, the temporal resolution of a conventional PCS is around 500 fs, as imposed by the photoconductive gate duration.
2) The maximum value of $dh(t'-t)/dt$ is proportional to the mobility of a material. Therefore, this technique can provide a much larger amplitude of the signal over the conventional impulse sampler by a factor of 10 to 100 if we use an undoped, low-defect material to exploit the highest mobility. On the other hand, the conventional impulse sampling technique must use a highly-defected, very low mobility material to provide a short-duration sampling gate.
3) The signal amplitude is proportional to τ for both the impulse and step-function sampling techniques. Therefore, the step-function technique can give a larger signal by varying τ, while the τ of the conventional impulse technique is equal to the material recovery time that cannot be adjusted easily.

V. Verification by Experiment

For the verification of the concept of step-function sampling, we have fabricated a coplanar stripline with a photoconductive gap on undoped GaAs that has a high mobility and a long carrier lifetime of a few hundred picoseconds. A short electrical pulse is generated between the lines of the coplanar strip in a region that is doped with amorphous

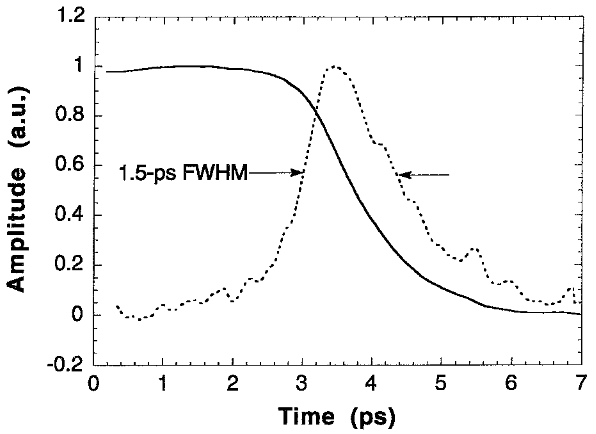

Fig. 2. The measured waveform using a step-function gate is shown with the solid line. The dotted line waveform is obtained by the subtraction of the measured waveform from the same measured waveform shifted by 100 fs.

Ge for the picosecond pulse generation. The step-function sampling gate on the undoped GaAs layer is 1.0 mm away from the generation point as shown in Fig. 1. The measured waveform using a step-function gate is shown by the solid line in Fig. 2. The dotted line waveform is obtained by the subtraction of the measured waveform from the same measured waveform shifted by 100 fs. The result shows the reconstruction of the picosecond electrical pulse from the step-function measurement. The rise time of the pulse is 1 ps and the full-width-at-half-maximum (FWHM) is 1.5 ps. The pulse is broader than the measurement resolution of 100 fs. That is not due to the measurement limitation, but to the dispersion of the electrical pulse propagating on the stripline. Another reason is due to the electrical pulse generation using amorphous Ge, which has a carrier lifetime of over 1 ps.

VI. Conclusion

We have demonstrated the measurement of picosecond electrical pulses using the photoconductive step-function sampling technique analytically and experimentally. This technique has the advantages follows: 1) Time resolution can be as short as 100 fs, as determined by the laser pulse width; 2) An undoped, high-mobility material can be used for the step-function gate. The high-mobility gives high measurement sensitivity; and 3) The gate duration is arbitrarily adjustable by the user.

Also, this technique is more suitable for photoconductive on-wafer sampling of microwave and millimeter-wave devices than the impulse sampling technique. This is because the impulse method needs a short-duration gate that cannot be easily fabricated on typical circuits wafers.

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