SANDIA REPORT
SAND2019-12671
Printed October 2019

Sandia National Laboratories

Microwave Doppler Charge Velocimetry for Narrow and Wide Bandgap Semiconductors

Eric Shaner, Chad Stephenson, John Klem, Clark Kadlec, Michael Goldflam, Dan Wasserman

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Characterization of vertical transport in semiconductor heterostructures is extremely difficult and often impractical. Measurements that are relatively straight forward in lateral transport using Hall methods, such as quantifying carrier density or mobility, have no analog in conventional vertical devices. Doppler charge velocimetry may provide an alternative approach to obtaining transport information. We hypothesize that we can drive vertical currents in structures like heterojunction bipolar transistors or nBn detectors, illuminate them with microwaves, and directly measure the carrier velocities through Doppler shifts imparted on the reflected microwave signal. Some challenges involve providing optical injection and working in the vertical geometry required to extract the desired information. While progress was made to this end, experiments have not yet proved successful. Implications for infrared material characterization are summarized at the end of this document.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DLTS	deep level transient spectroscopy
nBn	n-type, barrier, n-type based detector
SLS	strained layer superlattice
EBIC	electron beam induced current
PIN	p-type, intrinsic, n-type
EMI	electromagnetic interference
TTL	transistor-transistor logic
FTIR	Fourier transform infrared spectroscopy
LDV	laser Doppler vibrometry

1. OVERVIEW

There are numerous material metrology gaps where realizing vertical Doppler charge velocimetry would have significant impact. One example is nBn infrared detectors based on Type II superlattices. In this material system, the effective vertical hole mobility trends towards zero at relevant operating temperatures indicating charge localization [1]. Our current experimental technique for determining vertical mobility is to first measure two parameters, minority carrier lifetime and diffusion length, independently in specialty structures. One can then calculate the diffusion coefficient of the charge carrier which is directly related to mobility. Measuring field dependent velocities directly through Doppler shifted reflections would present an interesting alternative that could create new research opportunities such as real-time observation of radiation damage effects on transport in device structures.

Our experimental approach is based on a microwave reflectance apparatus we have developed for minority carrier lifetime measurements where we monitor changes in the reflected microwave signal in response to a laser pulse that generates free charge in the semiconductor. These free carriers injected into the material act as a mirror where the reflected signal amplitude is proportional to the lateral conductivity. We then monitor recombination processes by temporally resolving reflected microwave power. The concept behind this proposed idea is to induce vertical (growth direction) movement of the free-carrier mirror, and then sense Doppler shifts in the reflected microwave frequency to quantify the vertical velocity.

2. APPROACH

In past efforts, we have developed cryogenic minority carrier lifetime measurements and analysis based on time-resolved microwave reflectance. The bulk of our previous work relates to narrow bandgap materials, but this approach is material agnostic. From temperature dependent lifetime measurements, we have predicted device dark currents and fully characterized Auger recombination, background doping density, radiative coefficients, and Shockley-Read-Hall trap energy levels in numerous materials. The latter is particularly important for narrow gap materials as conventional DLTS approaches do not work well in this regime (due to leakage issues). By combining lifetime measurements with vertical diffusive transport characterization, we have previously demonstrated vertical mobility measurement in narrow gap Type-II strained layer superlattice (SLS) [1]. The results of those experiments provided strong evidence for charge localization at low temperatures that we hypothesize is due to interface fluctuations and alloy clustering [2].

Vertical mobility is straight forward to extract from carrier diffusion. If one knows the diffusion length in a material, and the minority carrier lifetime, one can obtain the mobility through the Einstein relation [3]:

$$D = \frac{kT}{q}\mu = \frac{L_D^2}{\tau_m}$$

Here D is the diffusion coefficient, k is the Boltzmann constant, T is temperature, q is the charge of an electron, μ is mobility, τ_m is the minority carrier lifetime, and L_D is the diffusion length. A problem here is that the diffusion length, L_D, is difficult to measure. We currently have two approaches that require custom device fabrication. For devices with a vertical charge extraction layer, one can perform electron beam induced current (EBIC) measurements that quantify the diffusion length [4]. These measurements require destructive cleaving of the sample and mapping the device current response to an electron beam as the cross section is scanned. Temperature dependent measurements, as well as data interpretation, are difficult. The other approach we have recently developed is to grow the SLS into the base of a heterojunction bipolar transistor geometry [1]. This type of device allows us to directly explore minority carrier transport in the base, however, the structure itself is not a detector and so while it is a good platform for material study, other key parameters such as detector dark current cannot be quantified within those growths. In short, this is the best we can do without another approach.

If by using Doppler velocimetry we can directly measure carrier velocity under a known drift electric field, then we can quantify mobility by noting $\mu = v/E$ where v is carrier velocity and E is the applied electric field [1]. The microwave reflectance measurements we routinely perform use the experimental arrangement shown in Fig. 2-1, which consists of a microwave source, circulator, and detector to illuminate a sample with 100 GHz radiation. For lifetime experiments, one uses a pulsed laser to generate e-h pairs in the material under test. This generated charge then forms a ‘microwave mirror’ that reflects microwaves back through the circulator. We then monitor the reflectance decay, as shown in the trace of Fig. 1, to quantify the lifetime of the excess charge.

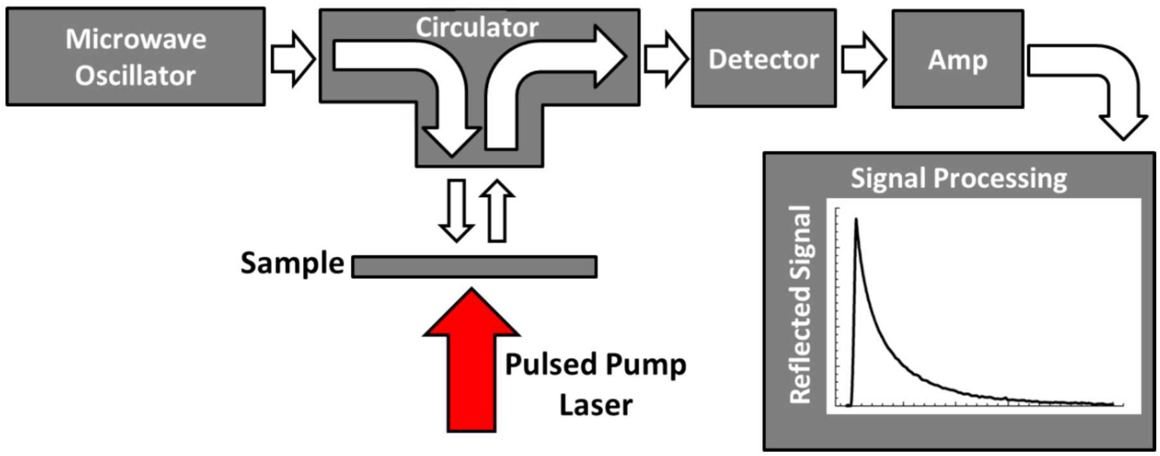

Figure 2-1 Time-resolved microwave reflectance experimental setup. We currently operate at 100 GHz microwave frequency and use high speed direct detection to time-resolve the impulse response to optical excitation and measure minority carrier lifetime. The microwave oscillator module includes an isolator. Our measurements are compatible with cryosystems and we routinely operate from 10K to room temperature.

The basic expression for the back reflection Doppler frequency shift with a stationary source is given by [5]

$$\Delta f = \frac{2v}{c} f_o$$

where Δf is the observed frequency shift, v is the carrier velocity, c is the speed of light, and f_0 is the microwave drive frequency. In our case, f_0 will nominally be 100 GHz and we expect carrier velocities to be in the ~10^4 cm/s to 10^6 cm/s range. This will result in frequency shifts ranging from ~100 kHz to 10 MHz imparted on the reflected microwave signal, values that are in principle easily measured. An important reference (Ref [6]), that will be discussed in more detail, demonstrates the general microwave Doppler principles using germanium for lateral mobility measurements.

3. RESULTS

Over the course of this project there were many failed attempts at observing the Doppler shift of back-reflected microwaves. Ultimately, this was due to poor experimental configurations and in some cases, as will be discussed in Sec. 4, the use of sample geometries that could not possibly have provided the desired Doppler response signal. Here, Ref [6] provides insight that should guide any future work in this area. In this section we will provide basic descriptions of what did not work, a geometry using Ge that we believe will work, and finally analysis of the range of material parameters we believe a Doppler approach could possibly extract in infrared materials of interest.

3.1. Pulsed response

Our initial experimental setup utilized the Sage Millimeter SSM-94313-S1 Doppler Sensor Module. This apparatus operates at 94 GHz and includes a source, directional coupler, circulator, and mixer. While intended for RADAR measurements this system is also suitable for our purposes. The output of the SAGE system was connected to a lens horn antenna design for operation at 94 GHz having an 80 mm working distance. The basic system is shown in Fig. 3-1.

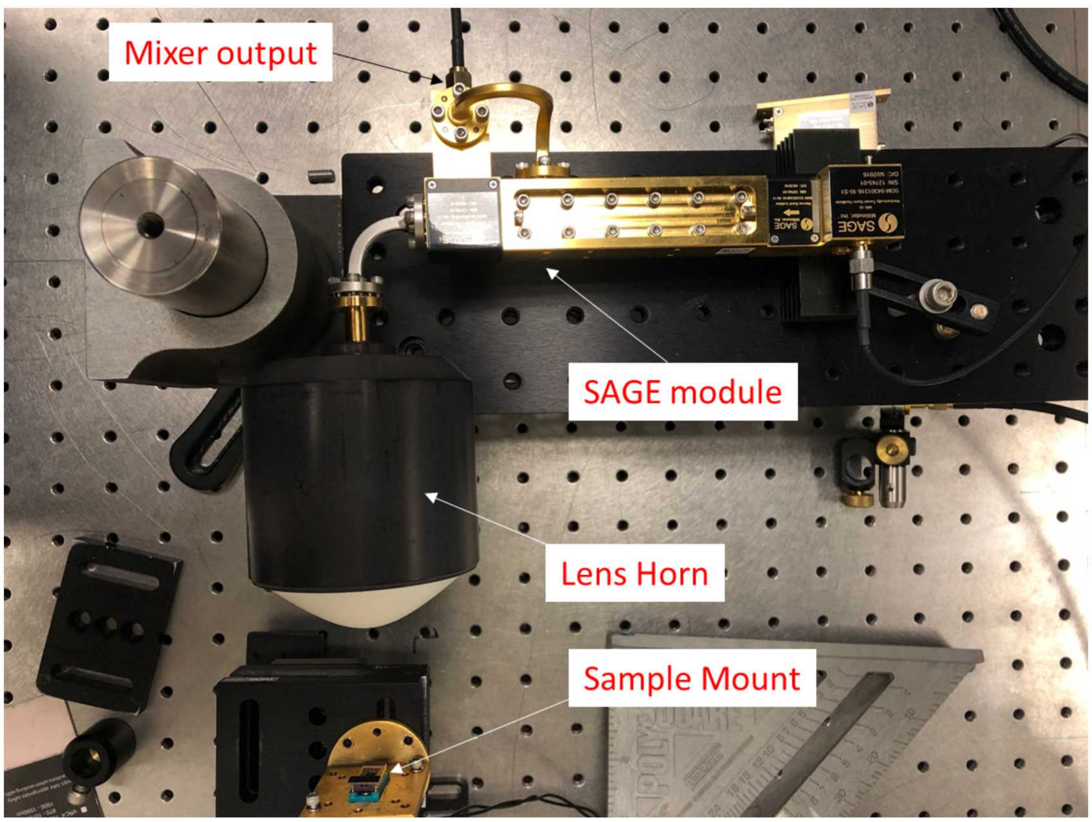

Figure 3-1 Basic Doppler measurement setup.

A simple first test of this system was to perform basic pulse decay lifetime measurements. This was accomplished by bringing a laser beam in at an angle to strike the sample, which in this case was a midwave material with ~5 micron bandgap. The blue trace shown is a single acquisition while the black trace is an average of several hundred scans. The system functioned as expected. The pulsed excitation was ~1 uJ @ 1535 nm.

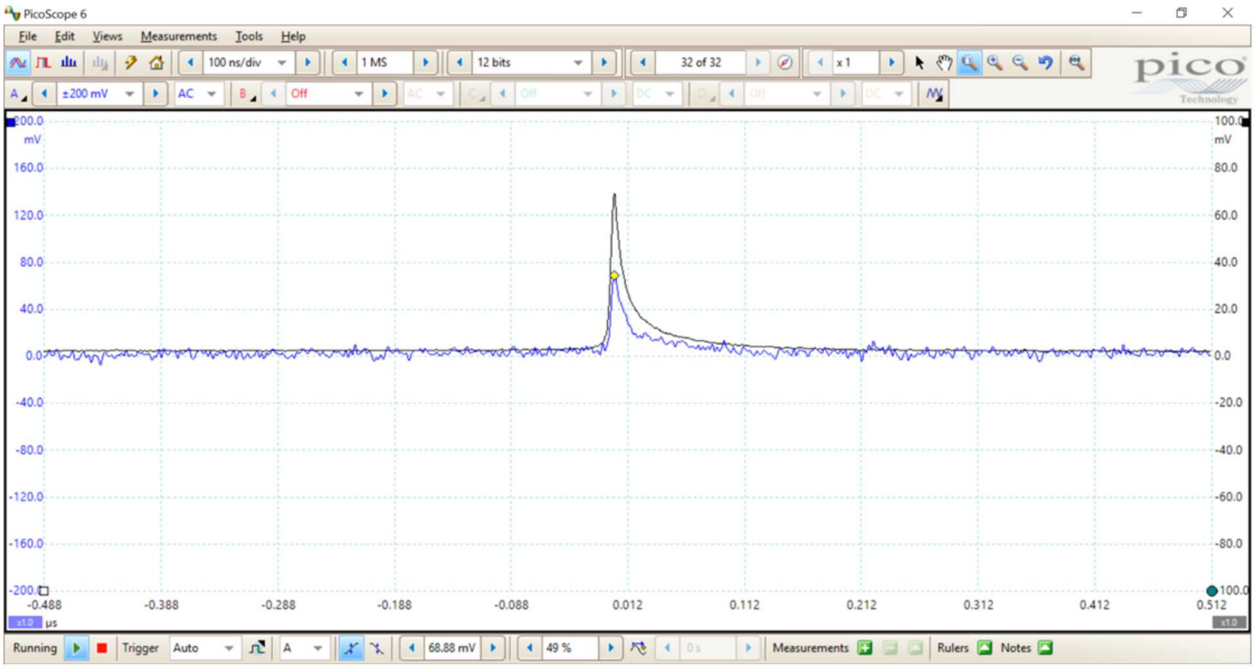

Figure 3-2 Time-resolved microwave response to pulsed excitation of the sample.

3.2. PIN Sample

Initial attempts at observing a Doppler shifted return signal utilized a GaAs PIN sample with no optical excitation. As shown in Fig. 3-3, the pulsing of the PIN sample does cause a change in the microwave reflectance, however, there is no Doppler ringing associated with the response. It is notable that driving current in the devices created a change in the reflected microwave signal. Later in the project, it became clear that only a moving charge front should impart any Doppler shift to the return signal and simply pulsing a PN junction should not produce any Doppler response. Pulsed laser charge injection experiments were also attempted on these samples that resulted in no observable Doppler response.

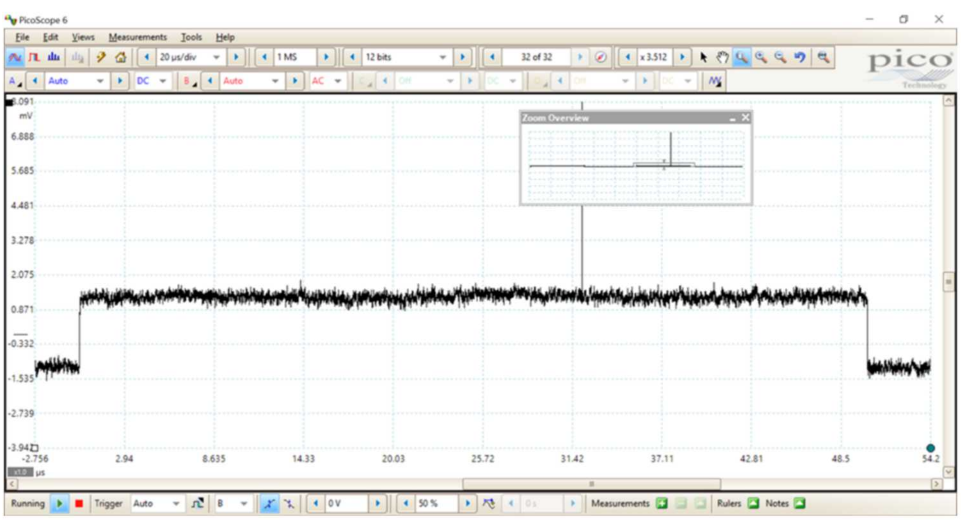

Figure 3-3 Microwave reflectance response to pulsed PIN junction under forward bias.

3.3. GaAs Resistor

Due to failures in early experiments with PIN structures, we decided to work with resistor restructures and designed a special vertical resistor structure in GaAs designed to optimize current spreading. In principle, this sample design is similar to the resistor geometry of Ref [6]. The structure grown start with n+ substrate followed by 20 microns of 1E15/cm^3 doped GaAs, capped with 1 micron of 4E18/cm^3 doped GaAs. This design provided for ~30% current uniformity over a 500 micron diameter circular opening. We then fabricated honeycomb aperture samples as shown in Fig. 3-4 with varying numbers of cells in order to allow for sample biasing while still enabling microwave access to the underlying material. Samples fabricated used 1 to 7 hexagon units. Figure 3-4 shows optical microscope images of a 7 unit and 3 unit device. It was unknown how much open area was required to give usable microwave access to the underlying material. Honeycomb widths of 250 microns and 500 microns were patterned.

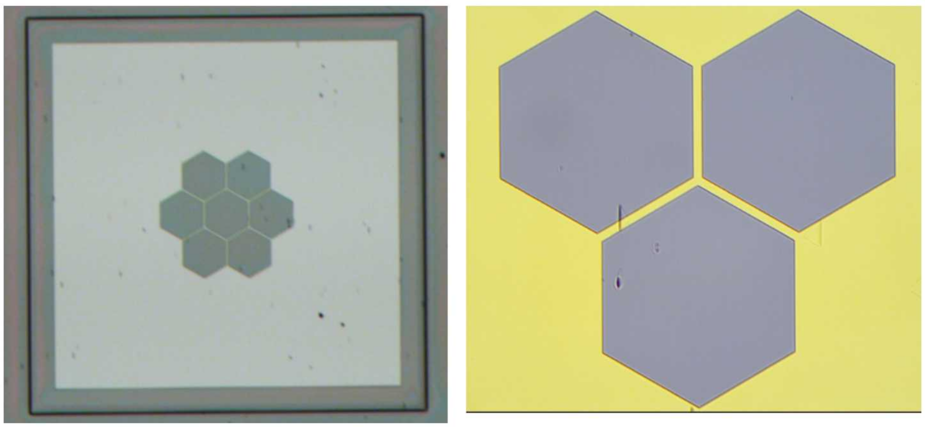

Figure 3-4 Examples of fabricated honeycomb samples on GaAs resistor material.

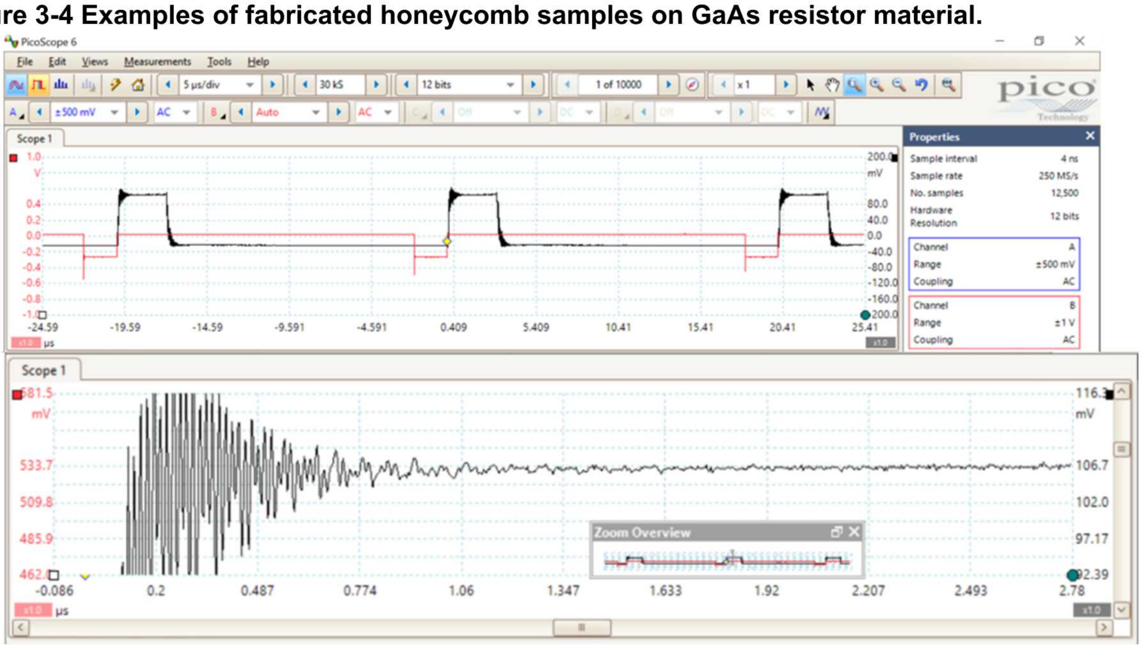

Figure 3-5 Examples of fabricated honeycomb samples on GaAs resistor material. Red trace is the trigger signal (sample pulsed on rising edge) and the black trace is the microwave response. The zoomed response in the lower panel highlights the ringing occurring when the sample is pulsed.

The microwave response to pulsed electrical excitation of the resistor sample is shown in Fig. 3-5. Clearly there is ringing at the rising and falling edges of the black trace which is when the sample was pulsed and relaxed. This ringing is all due to EMI and impedance mismatches and has nothing to do with any Doppler response. There is a microwave response to biasing the sample, the but the ringing components are simply experimental artifacts.

3.4. Germanium experiments

While previously mentioned experiments showed sensitivity of the microwave reflection to electrically and optically pulsing the devices, there was no sign of any Doppler response. It was determined that we should revisit the experiments of Ref [6]. In Ref [6] a long (50 mm) bar of either n or p-type Ge was placed inside a microwave waveguide. The ends of the bar were biased to apply an electric field and a side contact was used to electrical inject minority carriers. In those experiments, a Doppler return from the injected minority carriers was clearly observed and used to extract mobility. This is different from our experiment in two main ways: 1) we are attempting a free space vertical measurement as opposed to lateral waveguide measurement and 2) we are optically injecting charge rather than electrically injecting it. That said, the work of Ref [6] shows that obtaining a Doppler return signal should be possible at room temperature from Ge. In hindsight, it would have been good to start with attempting to repeat the experiments outlined in Ref[6].

The samples fabricated for this experiment utilized the same honeycomb mask set as the GaAs resistor experiments. One difference in the device design compared to the GaAs attempts was that both the top and bottom sides of the samples were patterned. This was to allow for optical injection at either the top or bottom interface as shown in Fig. 3-6. Several Ge wafers were used, both n-type and p-type <20 Ohm-cm, which is similar to the material studied in Ref [6].

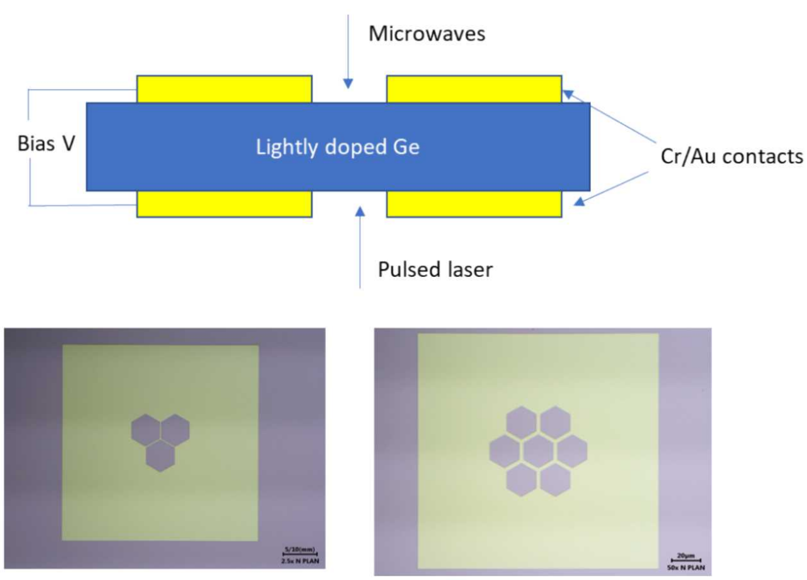

Figure 3-6 Experiments using Ge. Upper panel, basic double-sided sample patterning to allow laser access from either side. Lower panel, microscope images of fabricated honeycomb patterns on Ge.

Many attempts were made to extract a Doppler signal from these samples. One attempt is shown in Fig. 3-7 where an electrically triggered 1550 nm diode laser was used as the injection source and no bias is applied to the sample. Clearly, there is ringing coincident with the sample excitation which is due to EMI from the pulsed laser. Attempts were also made with a 650 nm electrically triggered pulsed diode laser (laser failed) and 1550 nm passive Q-switched laser.

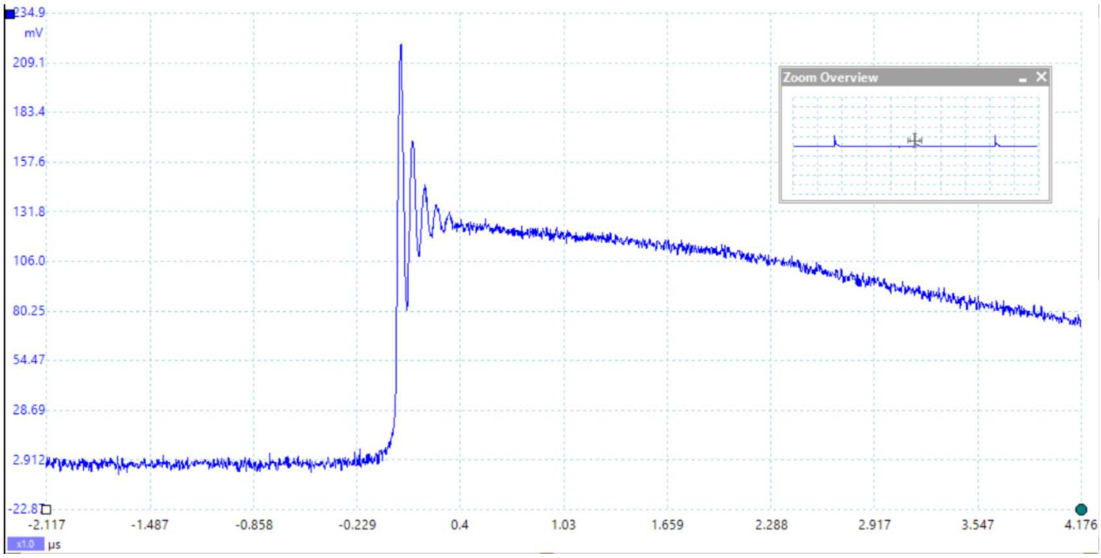

Figure 3-7 Microwave response to pulse 1550 nm diode laser excitation of Ge sample.

A problem with passive Q-switched lasers is that one cannot predict the pulse timing if TTL pump laser control is not available. This makes deriving triggers for other signals, such as the pulsed excitation of the sample, difficult. However, passively Q-switched lasers produce very little EMI to interfere with the rest of the experiment. Attempts were made to first optically pulse the sample, and the derive a trigger from that pulse to time electrical pulsing of the sample in order to apply the drift field. Large ringing was observed when the sample is electrically pulsed, like that shown in Fig. 3-7.

What was learned from these experiments (3.2, 3.3, 3.4), along with Ref [6], is that the following experimental setup is most likely to lead to success:

1) One must be able to electrically pulse the sample as DC biasing for drift at required fields will blow out sample in most cases.

2) One must be able to trigger the drift bias first, then provide injection due to ringing observed when bias pulse is applied. This makes Q-switched lasers challenging if they cannot be triggered.

3) The injection must be spatially abrupt and injection level must be low.

4) One most likely needs Q-switched pulsed laser for environmentally quiet charge injection.

Point 1 is not appreciated until experiments are attempted. The work of Ref [6] applies a voltage pulse to the Ge bar sample in order to apply the drift field without describing why. The reason is one can easily dissipate Watts in the sample under DC bias which will overheat the sample. For point 2, the reason to pulse the drift field bias prior to charge injection is because it will create ringing when applied (in all signals, including microwave return) that will make Doppler frequency extraction difficult.

Regarding point 3, in experiments on Ge where 1550 nm pump light was used, the spacing between the microwave system and the sample could be varied and clearly there was reflectance signal coming from deep in the substrate. This is evidenced by dueling positive and negative signals due to interference effects with reflections coming from different locations within the sample. According to Ref [6], the injection level must be low enough to not significantly disturb the applied drift field (which makes sense). If the amount of charge one can inject is limited, it would be much better for charge injection to be concentrated into a thin layer. In addition, for microwave reflectance, one can get odd return responses if the reflector thickness is on the order of the wavelength of the microwaves used that in general make data difficult to interpret. If one were to continue these experiments in Ge, a laser at 532 nm would most likely be the right choice and give < 1 micron absorption length as opposed to ~50 microns at 1550 nm.

Point 4 is something completely independent from the electrical injection scheme used in Ref [6]. Here we need to consider the nature of the pulsed laser source. If one cannot carefully impedance match the sample to electrical connections, as well as provide very good EMI shielding of any electrical pulsed laser, one will inevitably get ringing when either the drift bias or laser pulse is applied. A Q-switched laser, preferably passive, would be the quietest source to use. It should be noted that a passively Q-switched laser is compatible with point 2 if the digitizer employed can be triggered off the laser pulse and providing that the Q-switched laser a least has a TTL input for controlling the pump laser. This type of pulsing is different than active Q-switched lasers that use an AOM where the triggering of the AOM can also create electrical noise. Another option with a passive Q switched laser that does not have TTL triggering is to fiber couple it and use enough fiber (~100 meters) to provide a temporal delay such that the pulse will excite the sample after the electrical pulse is applied. The pulsing of the drift bias is only to avoid sample damage or heating, so precision timing of the drift bias pulsing in terms of jitter is not critical.

3.5. Absorption Measurements

Microwave detection techniques, such as microwave reflectance, can potentially be used in all scenarios where one would normally defer to PL or FTIR based characterization as the only alternatives. Microwave measurements sense the presence of free charge within the material and in general can be done in a completely non-contact manner (no devices required).

The main goal of a PL measurement is to identify the bandgap of the material by absorbing photons above the bandgap and waiting for them to trickle down to the band edge and emit light that is analyzed by an FTIR in the case of infrared materials. In highly defective materials, the PL signal-to-noise is often too low for successful measurements. The microwave reflectance version of this experiment is to monitor microwave reflectance amplitude while tuning a pump laser (from 2-12 microns), and directly observe variation in charge generated by the laser through changes in the microwave amplitude to locate the band edge of the material. While this approach requires a widely tunable laser, it may be possible with refinement to use the broadband FTIR source output for carrier generation and implement the microwave reflectance as a new kind of FTIR detector, where charge, not infrared photons, are sensed.

An example of the microwave reflection response of a semiconductor to a pulsed laser is shown in Fig. 3-8. Here, as indicated in the plot legend, the pulse energy was tuned to explore both high-injection as well as low-injection carrier dynamics. While for minority carrier lifetime analysis, one cares about the long-time duration tail decay, for the technique shown here we would only be concerned with the initial peak of the response. In Fig. 3-9, this initial peak response is plotted for two different InAsSb samples that did not have observable PL signals, but that were designed to have a bandgap near 8 µm. The wavelength of the pulsed laser was tuned and the initial peak response is plotted vs wavelength. Clearly at wavelengths shorter than 8 µm, the tunable laser wavelength is above the band edge, generating carriers that are sensed in microwave reflection. In contrast at wavelengths greater than 8 µm, there is minimal response suggesting a lack of carrier generation and therefore, no photon absorption. It is worth noting that the general shape of this photoresponse vs wavelength matches the expected absorption coefficient behavior. This can be considered as proof-of-concept that, if further developed, could lead to direct absorption coefficient extraction from these types of measurements. While the focus of this demonstration was on infrared (2-12 micron) wavelengths, it should be noted that these techniques in general are wavelength agnostic.

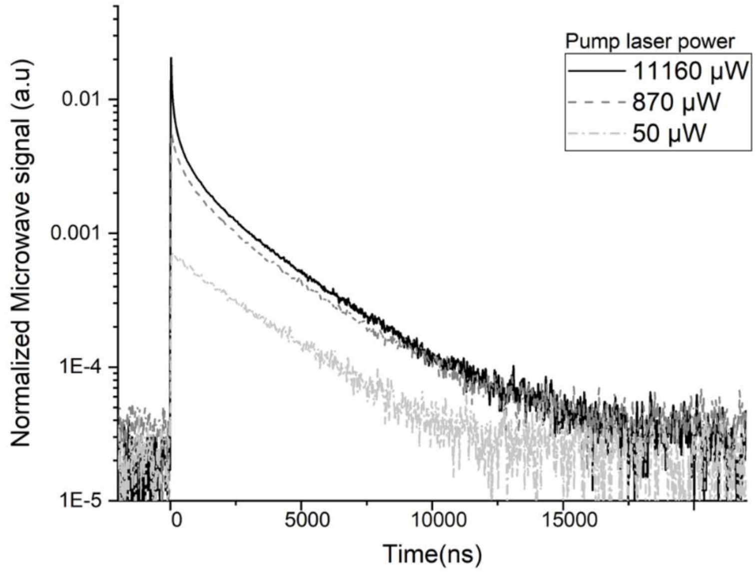

Figure 3-8 Microwave reflection response to a pulsed laser excitation of a semiconductor at various pulse energies. Example sample used was an InAs/InAsSb superlattice.

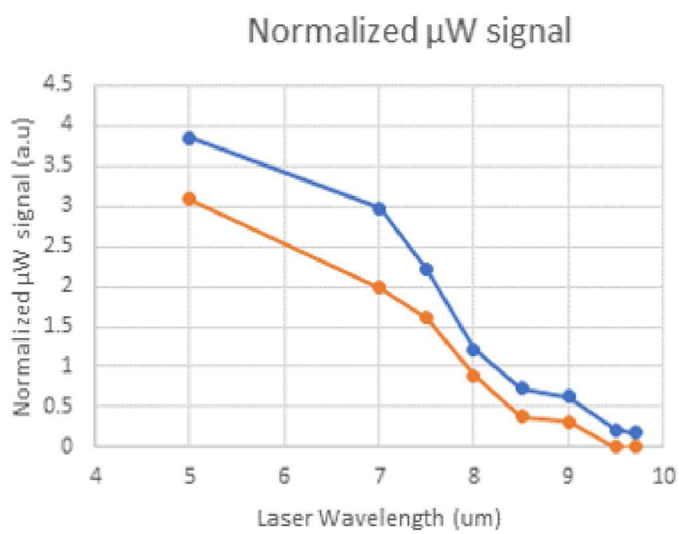

Figure 3-9 Peak microwave response to pulsed laser excitation of two different samples having unproven bandgap. Design intent of samples was to have a bandgap near 8 microns. Peak reflected microwave response was normalized to the photons per pump pulse for each data point.

3.6. Phase Issues

There was a thought after failed experiments that an issue was averaging multiple samples without having the source phase-locked to the pulsing of the samples. As a result, a phase locked system was developed where the microwave source was generated from a 10 MHz clock that could then be used to synchronize triggering for sample pulsing. We will not go into the details of that system as it was not necessary.

The beat term for a Doppler shifted signal mixed with the local oscillator can be described by:

Frequencies: $w_1 = source$, $w_2 = source \pm 2 * source * v/c$
Beat Term: $\sin(w_1 t)\sin(w_2 t + \emptyset) \rightarrow \cos(w_1 - w_2 - \emptyset) + \ldots$ ignore higher frequency terms

As shown, the phase term from the reflected wave carries through to the difference frequency beat note. Initially, it was thought that this meant the source needed to be phase locked to the rest of the experiment. However, it was later realized that the source phase wraps and the only meaningful phase that can carry over to the beat note is a single wave of the local oscillator. This results in the maximum phase error, due to experimental triggering, of the return signal being $(2 * v/c) < 10^{-4}$.

4. IMPLICATIONS FOR INFRARED MATERIALS

In Sec 3.4, some simple rules were outlined for having an improved chance of success at measuring vertical transport Doppler shifts for Ge. These rules are based on experimental failures as well as the work of Ref [6] that demonstrated Doppler measurements successfully in a different geometry.

The intent of our effort was to develop a technique relevant to measuring common infrared detector materials. Typically, these are growths ~10 microns thick. If we define the criteria for resolving a Doppler signal to be observing one period of an oscillation (Ref [6] easily observed 4-5 oscillations), it can be shown that the sample must be thicker than one half of the source wavelength. At 100 GHz, this would be 1.5 mm in free space. If we assume a refractive index of 4 this thickness is reduced to 375 microns, so clear Doppler signals should be possible to obtain from Ge substrates (500 microns thick). However, 10 micron thick epilayers are far too thin to be successfully measured with the assumption of a full period of the Doppler frequency needing to be resolved.

In the field of laser Doppler vibrometry (LDV), picometer displacement resolution is often specified [7] when using a laser source of 632 nm wavelength. This performance is achieved through careful tracking of the phase of the signal reflected from an object [8]. Doppler shifts from a moving surface can be thought of as reflecting from the moving arm of a Michelson interferometer. Rather than mapping out a full wave of the Doppler signal, a partial fringe can be mapped and translated into the object displacement. However, it is unlikely that such phase tracking can be done in any reasonable manner when the source of the reflection is a transient sheet of optically injected charge. That scenario is significantly different from monitoring the reflection return from an object with fixed reflectance that happens to be moving.

There could be some benefit in moving to higher frequency in order to reduce the minimum sample thickness required given the full wave assumption. The plasma frequency of the material of interest imposes a restriction on the maximum frequency that can reflect from the injected charge density. For common background carrier densities in relevant infrared materials, on the order of 1E15/cm^2, the plasma frequency is ω_p~2π x 400 GHz for electrons. This frequency is not sufficiently high to allow for measurements of the thin layers of interest.

5. CONCLUSION

This project explored the possibility of using Doppler velocimetry, measured through microwave reflectance, to directly quantify charge velocity in the vertical (growth) direction and thereby obtain vertical mobility. Throughout the effort, there was no clear evidence of a Doppler shifted return signal, however, we have provided some guidelines that should allow observation of a Doppler shifted signal in Ge. Our hope when this project began was that a technique could be developed that would be applicable to quantifying vertical transport in materials relevant for infrared detectors. However, after gaining a better understanding of what is required for successful measurements, this technique does not look promising due to the epilayer thickness in relevant materials being too thin, and carrier densities too low, to support probing of velocities using a Doppler approach.

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