

RF Read-Out of Minority Carrier Lifetimes in Micro-Scale Infrared Materials

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Abstract: We present micro-scale time-resolved microwave resonator response (μ -TRMRR), a sensitive technique capable of measuring carrier lifetimes in micron-scale materials, something not typically achievable using common techniques like time-resolved photoluminescence or time-resolved microwave reflectance.

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1. Introduction

Minority carrier lifetime is an extremely important material parameter providing invaluable insight into material quality, nonradiative recombination mechanisms, and the potential bandwidth of detectors or other optoelectronic devices. Typically, measurement of these lifetimes is performed using non-invasive, contact-free methods, as the fabrication of strictly ohmic contacts can be non-trivial for nanostructures, polymers, or 2D materials. Two popular contact-free lifetime measurement techniques are time-resolved photoluminescence (TRPL) and time-resolved microwave reflectance (TMR). In TRPL, a laser pulse excites electron hole pairs (EHPs) in the semiconductor material, and the resulting emission via radiative recombination of EHPs is measured as a function of time, from which a carrier lifetime can be extracted [1]. However, TRPL requires both that the material emits efficiently (which is problematic in the IR [2]) and that the collecting detector be high-speed, and sensitive to the wavelengths of sample emission.

TMR, an alternate technique which measures microwave reflection following pulsed illumination of the sample [3], has gained popularity, especially in the mid-infrared [4]. TMR offers high sensitivity to non-equilibrium carrier concentrations and is especially effective for samples that do not emit. However, the mismatch between the microwave probe beam cross-section and the dimensions of typically small samples prevents the pulsed optical excitation from significantly modulating the reflected microwave, resulting in poor signal to noise ratios for micron-scale samples. Here, we introduce the micro-scale time-resolved microwave resonator response (μ -TRMRR) technique [5], shown schematically in Fig. 1, which alleviates the challenges of TRPL and TMR, while offering improved sensitivity and ease of carrier lifetime extraction.

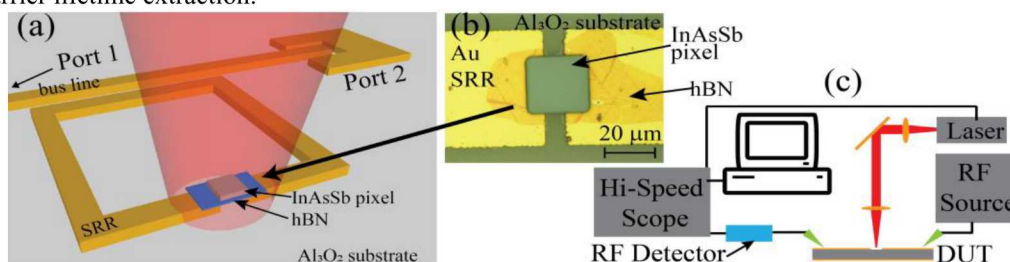


Figure 1 (a) Schematic of the SRR with pixel and hBN spacer; (b) micrograph of the SRR gap; (c) schematic of the experimental setup

By utilizing a microwave split ring resonator (SRR), we can strongly localize the RF fields in the SRR gap [6], where we can then place the material of interest—in this case, a one μm thick, $24 \mu\text{m} \times 24 \mu\text{m}$ pixel of indium arsenide antimonide (InAsSb) which is placed over a thin layer of hexagonal boron nitride (hBN) to reduce dark conductivity/capacitive loading effects, as shown in Fig. 1(a). The coupled pixel-SRR is driven on resonance by a continuous-wave RF source, and the pixel is then optically pumped with a fast laser; an RF Schottky diode detector collects the modulated signal which is sent to a high-speed oscilloscope to record the transient decay.

2. Experiment and Results

The SRR is fabricated on a 99.6% aluminum oxide substrate using standard lithography, evaporation (10/500 nm Ti/Au), and liftoff techniques. One micron of InAsSb is grown on a sacrificial aluminum arsenide antimonide layer

(lattice matched to a GaSb substrate) via molecular beam epitaxy (MBE). Pixels are fabricated [7] from this material and are then placed in the SRR [8]. The sample is housed in an ARS cryogenic probe station, and is pumped with a 1064 nm, 1 ns laser emitting approximately 6.8 μJ per pulse with a repetition rate of 10 kHz. Temperature dependent decay curves, with excellent signal to noise ratios, are shown in Fig. 2(a).

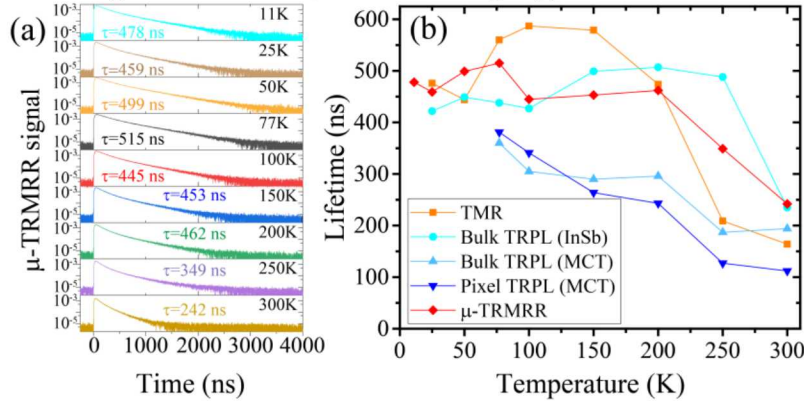


Figure 2 (a) Temperature dependent transient decay curves with extracted lifetimes shown; (b) extracted temperature dependent carrier lifetimes from $\mu\text{-TRMRR}$, bulk TRPL (MCT & InSb), large pixel cluster TRPL (MCT), and bulk TMR

We compare our extracted single-pixel $\mu\text{-TRMRR}$ lifetime to that of TRPL and TMR in Fig. 2(b). Note that while both TRPL and TMR could only be performed on the bulk material or a large cluster of pixels, our technique allows for lifetime measurements of a single pixel. When using an MCT (~ 4 ns response time), we calculated approximately 16.6 nJ of absorbed energy required to obtain a resolvable signal in the TRPL experiment compared to only 35.5 fJ of energy required in the $\mu\text{-TRMRR}$, resulting in a $> 10^5$ improvement in sensitivity. Furthermore, as seen in Fig. 2(b), extracted lifetimes using the MCT are inaccurate, as the signal falls below the noise floor of the system before the low-injection condition is satisfied. However, when using a more sensitive InSb detector (but with a slower ~ 23 ns response time), the extracted bulk carrier lifetime closely matches with our $\mu\text{-TRMRR}$ result, which is also very close to TMR performed on bulk material. Hence, our $\mu\text{-TRMRR}$ technique offers significant enhancement in signal to noise from orders of magnitude smaller samples, without compromising measurement accuracy.

3. Conclusions

In conclusion, we have shown a technique capable of measuring carrier lifetimes in micro-scale infrared materials, something not practically achievable using the popular TRPL and TMR techniques. To obtain a comparable signal to TRPL using a conventional MCT, $\mu\text{-TRMRR}$ requires $> 10^5$ less pump energy. Despite the difficulties in extracting accurate lifetimes in the mid-IR (especially from micro-scaled materials), $\mu\text{-TRMRR}$ results match well with lifetimes extracted from bulk TMR and TRPL measurements. The $\mu\text{-TRMRR}$ approach offers both sensitivity and accuracy and could enable lifetime measurements for any number of micro-scaled materials, including a range of 2D materials.

4. Acknowledgements

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