Femtosecond carrier dynamics in Ge/SiGe quantum wells

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We resolve photoinduced changes in carrier populations of Ge/SiGe quantum wells using femtosecond pump-probe spectroscopy. Absorption transients < 400fs indicate rapid $\Gamma \rightarrow L$ intervalley scattering that may explain exciton linewidth and suggest saturable absorber applications.

As photonics emerges as a viable technology for integration with silicon electronics, the need has grown for a more thorough understanding of the materials being used in such devices. A decade ago, interest was shown in understanding the ultrafast carrier dynamics of Ge and SiGe [1]. Recently, attention has again returned to these materials, now further stimulated by possible use in Si-compatible optoelectronics. Strong quantum confined Stark effect (QCSE) has recently been shown in Ge quantum wells (QWs) with SiGe barriers [2, 3]. An electroabsorption modulator has been fabricated using this materials system, which demonstrates the possibility of high-performance light modulators that are Si-compatible [4]. Using such a device structure, this work sets out to investigate a specific dynamic process in Ge/SiGe wells: the intervalley scattering of electrons in the conduction band from the direct Γ valley to the indirect L valley. Insight into this scattering time and the carrier dynamics that occur on similar timescales could lead to an understanding of the origin of the exciton linewidth in such modulators, and possibly to the development of a fast saturable absorber for laser modelocking (see, e.g. [5] for previous ultrashort pulse modelocking with SiGe mirrors).

In order to measure the intervalley scattering time of a Ge/SiGe QW structure, time-resolved transmission data was recorded using a pump-probe setup, shown in Fig. 1. The laser used was a short pulsed fiber laser with pulse width of ~ 120 fs, a bandwidth of 41 nm centered at 1550 nm,

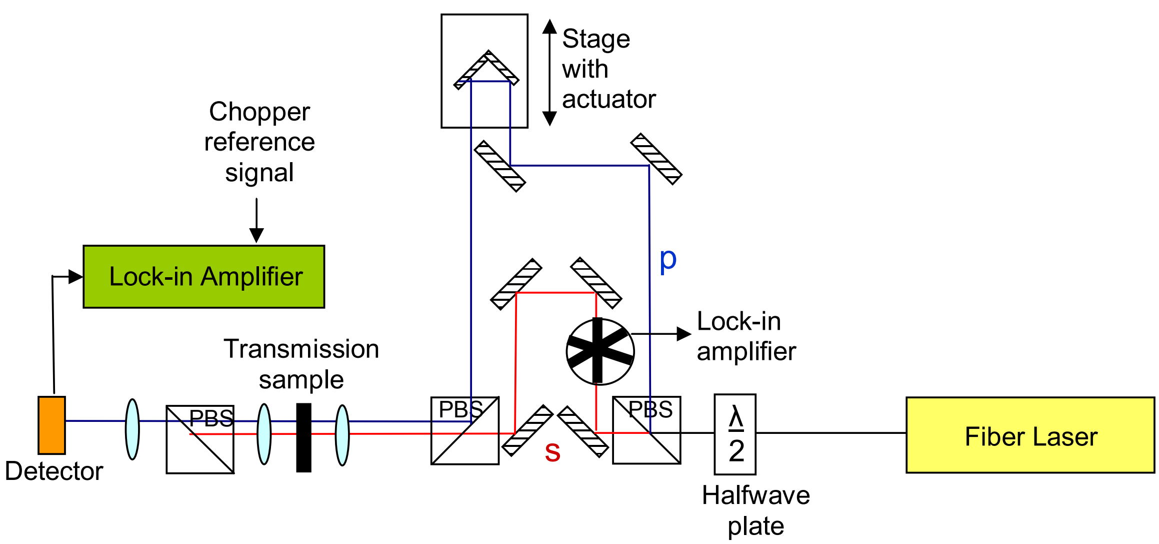

Fig. 1: The pump-probe setup used in this experiment. In this diagram, *PBS* denotes a polarizing beam splitter. *s* and *p* are the respective polarizations of the pump and probe beams.

and a repetition rate of 79.8 MHz. In the setup, the laser beam is initially split into the two different polarizations, *s* and *p*, corresponding to the pump and pulse beams respectively**.** The relative splitting of the beam power in each path can be changed by rotating the half-wave plate before the first polarizing beam splitter. The transmitted pump beam is substantially blocked by the final polarizing beam splitter, so the detector sees the transmitted probe beam, and the lock-in detects the change in probe transmission resulting from the effects of the pump beam in changing the sample transmission. To create a time delay between the pump and probe pulses, the probe beam path is diverted to an actuator stage, which is scanned in space to change the delay in time. Once the two beam paths are recombined, they are focused to a ~ 1.6 μm spot radius on the sample. The pump light has a fluence of ~ 3.2 pJ/μm^2. Using this configuration, changes in the transmission of the probe pulse induced by effects of the pump pulse on the sample are detected as a function of the relative delay between pump and probe pulses.

The device tested was a *p-i-n* diode structure fabricated on a Si substrate. The sample included 60 Ge quantum wells ~ 15 nm thick, each sandwiched between SiGe barriers, and contained within the nominally intrinsic (*i*) region of the diode. Further details of this sample structure are given in Ref. [4]. This particular structure was successfully used to demonstrate optical modulation [4]. As mentioned, the QWs display absorption that varies with electric field due to the quantum confined Stark effect (QCSE). Previously, the QCSE has been demonstrated in a similar structure to operate in the telecommunications C-band near 1550 nm by heating the device to temperatures compatible with CMOS operation [3]. Changing the temperature of the device was vital to the work presented here, because the wavelength of the ultrashort pulsed laser was not tunable. Thus, we tune the device to the laser center wavelength by a combination of heating and reverse bias. It should also be noted that due to the 41nm bandwidth of the laser, it was not critical for the exciton absorption peak to sit right at the laser's center wavelength of 1550 nm. In this work, the device was heated to 120°C**,** shifting the room-temperature, zero-bias exciton peak by 85 nm to ~ 1540 nm.

For zero or small applied biases, we see a strong bleaching soon after the point of zero delay between the pump and probe beams, followed by a strong recovery (Fig. 2). Because of the large valence band density of states we expect relatively little bleaching of absorption associated with filling the valence band states, and we also do not expect any rapid change in the hole populations on a sub-picosecond timescale [1]. We expect that the dominant absorption change on a sub-picosecond time scale is due to bleaching associated with the electrons occupying the direct Γ conduction band valley. Based on previous measurements in bulk Ge [1], we expect that electrons excited into the direct gap zone-center Γ conduction band valley may scatter on a time scale of hundreds of femtoseconds into the lower energy, indirect *L* valley, leading to a corresponding rapid recovery of the absorption bleaching.

We deduce an upper estimate for the electron intervalley scattering time based on fitting an exponential recovery to the absorption bleaching in data as in Fig. 2. In this specific case, at 1 V reverse bias, we can fit the recovery with a 367 fs exponential time constant. When the bleaching has recovered on this time scale, the transmission does not completely return to its original value. That incomplete recovery may be due to some slight remaining bleaching that results from the presence of holes near zone center in the valence band; there are no corresponding side valleys in

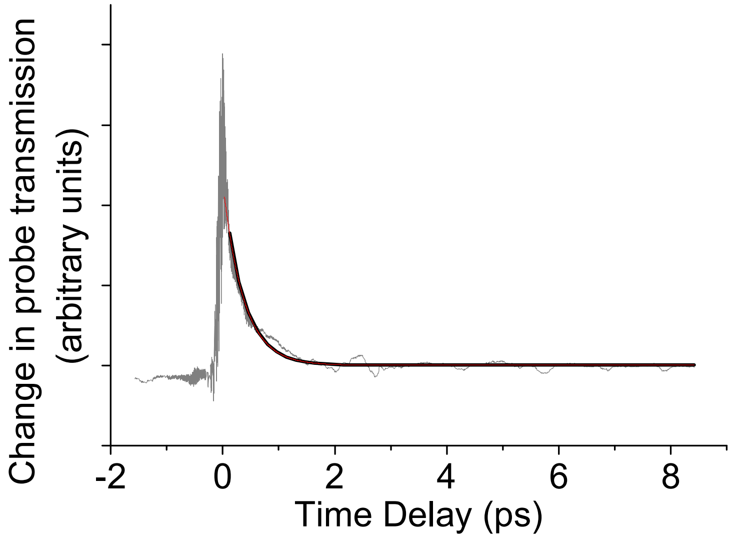

Fig. 2: Change in the transmission of the probe beam as a function of the relative time delay between the pump and probe pulses at 1 V applied bias and 120°C. The gray line is the actual measured signal and the black line is the best-fit exponential curve with a time constant of 367 fs.

the valence band into which the holes would scatter rapidly, and the holes may remain near zone center until they recombine with electrons or are swept out by the electric field.

The recovery time measured here is probably an upper limit on the intervalley scattering time. The direct optical absorption here only partly overlaps the spectrum of the laser, and so the effective pulse width corresponding to that overlapping portion may be longer, limiting the time resolution in our measurement. Our belief is that the exciton peak actually needs to be shifted beyond 1550 nm to fully absorb the energy in the laser pulses, which would allow for a more accurate measurement of the intervalley scattering time.

In conclusion, we have measured photoinduced changes in carrier populations of Ge/SiGe QW modulator structures using femtosecond pump-probe spectroscopy. An intervalley scattering time of < 367 fs is deduced for a 60 QW sample with a 1 V bias applied to it. This sub-picosecond scattering time has important implications for future work related to the exciton absorption peak in such modulators as it may be a major source of the finite linewidth of the exciton peak, and could also possibly lead to the development of a fast SiGe QW saturable absorber.

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