Impact of Mechanical Strain on Auger Recombination in InGaAs/InP

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Abstract: We characterized the impact of mechanically-applied biaxial strain on Auger recombination in InGaAs quantum wells using time-resolved photoluminescence. Our results support that Auger recombination is reduced by mechanical distortion introduced by strained-layer epitaxy.

1. Introduction

Auger recombination is a critical non-radiative loss mechanism in telecom-range quantum well (QW) lasers, limiting their temperature stability, threshold current, and efficiency [1, 2]. In InGaAs(P) QW lasers, Auger recombination can be mitigated via epitaxial strain, induced by varying the QW composition [3–6]. However, when strain is varied via the composition, so too is its chemical nature. Thus it is an open question whether laser performance is improved by mechanically-induced strain, chemical changes, or a combination of both. To directly address this question, we performed time-resolved photoluminescence (TRPL) as a function of applied mechanical strain on InGaAs QWs embedded in a flexible nanomembrane. Using TRPL, we recorded carrier recombination dynamics with high temporal resolution and fit the TRPL curves to determine the dependence of the Auger coefficient upon applied mechanical strain.

2. Experimental Setup and Analysis

The test heterostructures consisted of a stack of four InGaAs QWs with a compressive strain of -1.9% to the InP substrate. These QWs (Fig. 1a) were layered between AlGaInAs barriers and AlAsSb carrier blocking layers. A thin gold cap was deposited on the top layer, which was bonded to a flexible Kapton film coated with a thin layer of gold. The substrate was subsequently etched away, reducing the QW strain to -1.6%. For testing, samples were mounted in a biaxial stretcher, which applied a variable stress on the Kapton backing in two perpendicular directions. The induced QW strain was determined from the spectral shift in the steady-state photoluminescence (PL) QW emission peak.

A pulse-picked mode-locked Ti:Sapphire laser (9.5 MHz) was used as the pump source and TRPL was detected with a single-photon superconducting nanowire detector and a time-correlated photon counter. The emission spectrum was measured with an optical spectrum analyzer. For each of the three nominally-identical InGaAs QW membrane samples, TRPL traces were collected at varying pump fluences, corresponding to different peak excited carrier densities in the QWs. Applied mechanical strain was varied from 0 to 0.8% (corresponding to net QW strains ranging from -1.6 to -0.8%) using the biaxial stretcher and TRPL and spectral measurements were recorded at each applied strain value. This process was continued until the sample was stretched to the point of failure, signaled by a loss of PL or delamination from the backing.

To extract Auger recombination values from the TRPL traces, we take the equation for carrier decay as:

$$\frac{d}{dt}\left(\frac{n}{n_0}\right) = A\frac{n}{n_0} + Bn_0\frac{n^2}{n_0^2} + Cn_0^2\frac{n^3}{n_0^3} \tag{1}$$

for a carrier density n, a peak carrier concentration of n_0, and coefficients A, B, and C representing Shockley-Read-Hall (SRH), radiative, and Auger recombination, respectively. Rearranging the equation for the peak-normalized radiated luminescence, $J_{PL,norm} = n^2/n_0^2$, yields a solution with one-to-one correspondence to the TRPL traces [7]. Using nonlinear optimization, the A and C coefficients were fitted by numerically solving Eqn. 1 followed by convolution with the system instrument function. This provides Auger coefficients for each value of peak excited carrier density at each applied strain. In the degenerate carrier concentration limit that corresponds to the typical

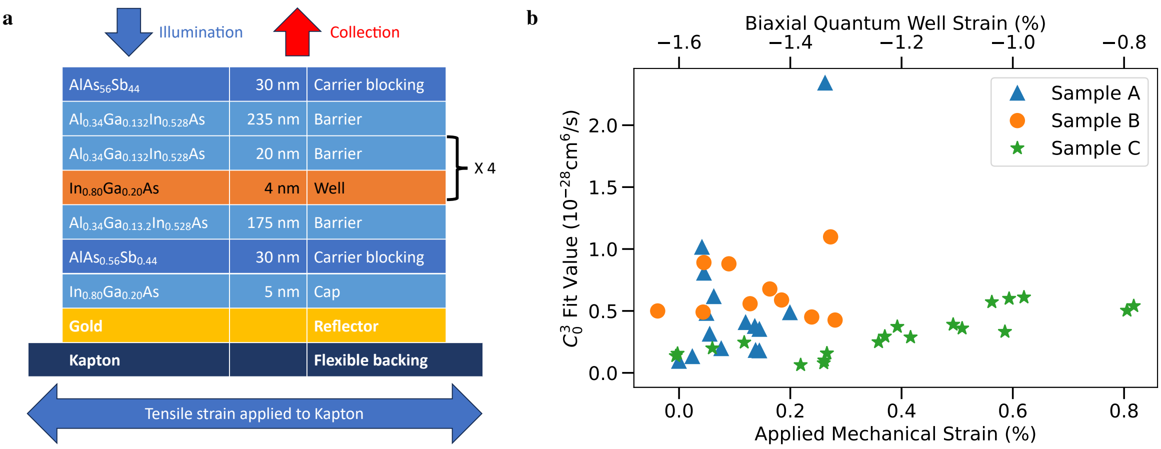

Fig. 1: (a) Layer structure of the InGaAs quantum wells (QW) after transfer. (b) Cubic Auger recombination coefficient in the low carrier density limit with applied mechanical strain. The most robust sample studied, Sample C, showed a strong dependence upon mechanical strain, consistent with theory.

semiconductor laser operating regime, Auger recombination takes the form $C(n) = C_1 n_0 + C_2 n_0^2 + C_3 n_0^3$ [8]. The cubic term is distinguishable from the SRH and radiative terms, and was ascertained at each applied strain level from the C values extracted in Eqn. 1 by fitting to:

$$C(n_0) = \frac{C_0^3}{1 + (n_0/n_c)^b} \tag{2}$$

where C_0^3 is the cubic Auger coefficient at low carrier density, n_c is the degenerate carrier density limit, and the exponent b is a fitting parameter [8, 9].

3. Results

For our three InGaAs QW samples, surface uniformity was observed with optical microscopy. Samples A and B exhibited significant cracking and rough surface while Sample C was noticeably more uniform. Not surprisingly, Sample C remained intact to higher applied strains than the other samples and TRPL measurements were successfully obtained up to 0.8% applied mechanical strain. Cubic Auger values obtained from fitting Eqn. 2 are graphed in Fig. 1b for all samples. Values were in the expected range for InGaAs QWs [4]. A clear dependence of Auger coefficient with mechanical strain was observed from Sample C, likely due to its more pristine nature. This work provides important support to the theory that mechanical strain contributes to the reduced Auger recombination observed in telecom range, strained-layer InGaAs(P) QW lasers.

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