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Clamping of the Linewidth Enhancement Factor in Narrow Quantum-Well GRINSCH Semiconductor Lasers

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The linewidth enhancement factor in single quantum-well GRINSCH semiconductor lasers is investigated theoreticaly and experimentally. For thin wells a small linewidth enhancement factor is obtained which clamps with increasing carrier density, in contrast to the monotonous increase observed for thicker wells. Microscopic many-body calculations reproduce the experimental observations attributing the clamping to a subtle interplay between excitation dependent gain shifts and carrier population distributions.

For many practical applications, a reasonably small and excitation independent linewidth enhancement (or antiguiding) factor (LWEF) is a highly desirable property for the semiconductor laser. The magnitude of this quantity influences the chirp of pulses in amplifiers and the degree of filamentation and hence, far-field broadening, in high power laser diodes. Therefore, one needs systematic studies of the dependencies of the LWEF on gain medium and laser structural properties.

The LWEF $\alpha(\omega)$ is a function of the density dependent laser material gain (which is proportional to the imaginary part of the susceptibility χ), and on the refractive index (which is proportional the real part)

$$\alpha(\omega) = \left(\frac{d\,\mathcal{R}e\{\chi(\omega)\}}{dN}\right)\left(\frac{d\,\mathcal{I}m\{\chi(\omega)\}}{dN}\right)^{-1}. \qquad (0.1)$$

Here, ω is the frequency and N is the total carrier density. Since gain and refractive index are fully determined by the semiconductor material composition and structure one may optimize $\alpha(\omega)$ to some degree by choosing suitable gain media. Furthermore, because of possible carrier leakage from the quantum well (QW) into barrier states in narrow QW-systems also the design of the laser structure is important [1,2].

In this work we use a microscopic theory for the laser gain medium. This theory is based on the semiconductor Bloch equations [3,4] where the damping and dephasing processes are treated at the level of quantum kinetic theory [3,5,6]. It has been shown previously, that this theory yields very good agreement with experimentally measured gain curves [7]. In contrast, calculations applying a simple phenomenological dephasing time as used in previous approaches [1,2] may yield incorrect gain dispersions and density dependencies. As discussed in Ref. [5], e.g., the gain maximum may shift in the wrong direction (red instead of blue). As will be shown in this letter, the density dependence of the gain maximum is crucial in determining the correct LWEF at the gain peak, where a

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laser typically operates. Thus, a microscopic description is required for reliable results.

For our present study we extended the earlier approach [3,5,6] to additionally include the effects of the energetically higher barrier states and of conduction-band nonparabolicities. In many laser structures these effects are particularly relevant to obtain the correct refractive index at a given carrier density. Clearly, the gain is predominantly determined by the states with inverted occupation propability. These are energetically close to the fundamental gap while gain modifications by the energetically higher states rapidly decrease with increasing detuning. On the other hand, the refractive index and therefore the LWEF is also strongly influenced by states energetically above the gain, i.e. in the absorptive region. Hence, under suitable structural and operational conditions not only the states confined in the QW but also the barrier states contribute significantly to the LWEF. [2]

Due to the relatively large width of the barrier region in most laser structures, its states are energetically very close, almost forming a continuum. Consequently, the Coulomb interaction between these states is different, i.e. more three-dimensional, compared to the rather widely separated quasi two-dimensional states that are confined in the QW. In order to describe these effects correctly, it is necessary to include the dependence of the Coulomb interaction on the confinement wavefunctions, i.e. to include the band-dependence of the Coulomb interaction. This has not been necessary in the calculations concentrating on gain only [5–7].

Whereas in previous approaches [1,2] states confined in the barrier have been approximated by a quasicontinuum, all states are treated at an equal level of accuracy within our model. Consequently, we have to include a relatively large number of bands in our calculations. For the highest densities and the laser structures investigated in this paper, this amounts to eleven hole and six conduction bands. As our calculations revealed, the qualitative behaviour of the LWEF as e.g. a clamping or monotonous increase with the carrier density is determined by the energeticly lowest bands. However, for a quantitative agreement with the experiment higher bands have to be included. For energies high above the bandgap, conduction band nonparabolicities become significant. Therefore, to describe the barrier states correctly and to obtain quantitatively reliable results, these nonparabolicity effects also have to be included.

We concentrate for the theoretical study on structures with a single $In_{0.2}Ga_{0.8}As$ QW with varying well width d_w. This type of well is typically used in high-power applications in the near infrared ($900 - 1000\,nm$). We assume a GRINSCH (graded index seperate confinement heterostructure), i.e. the QW is sandwiched between graded index $Al_xGa_{1-x}As$ layers where x rises from $x = 0.1$ to $x = 0.6$ over a distance of $85\,nm$. All calculations were made for TE-polarization and assuming room temperature ($300\,K$).

Fig. 1 shows the computed spectra of the LWEF function for different total carrier sheet-densities for $d_w = 3\,nm$ and $10\,nm$, respectively. The dots mark the peak gain energies at the respective densities. These calculations show two trends confirming earlier theoretical and experimental investigations [1,2,8,9]. First, the LWEF increases with increasing carrier density. Second, the LWEF at a given carrier density decreases with decreasing d_w [1,9]. The reason for the latter is the increase of the energetic distance between confined states for decreasing d_w. Thus, the contribution to the density of states of higher interband transitions is energetically shifted further away from the band edge. This leads to stronger (blue-) shifts of the chemical potentials for a given change in density. For the types of structures, temperature and densities regarded here, the electronic states contributing at energies close to the gain maximum are almost completely filled. The changes in the gain amplitude are almost exclusively due to changes in the hole distributions. Due to the higher density of states in the wider structure additional carriers can occupy states closer to the gain maximum than in the narrower well. This can be seen from the spill over of carriers from the QW into states in the GRINSCH region in Fig. 2. With increasing density, the fraction of carriers in the QW decreases for $d_w = 3\,nm$, whereas it remains almost constant for $d_w = 10\,nm$. Those energetically closer carriers have a stronger influence on the refractive index at gain maximum. Thus, the changes in the refractive index increase with the well width. Carriers at energies high above the gain maximum (i.e. here: in the second or higher bands) have only small influence on the gain at gain maximum. For both choices of d_w, the differential gain is given almost exclusively by the changes in the lowest subband and therefore rather independent of d_w (see Fig.3). Consequently, according to Eq. (0.1), the LWEF becomes smaller for lower d_w. For the cases investigated here, gain roll-over (which might complicate the argumentation) occurs only at densities far beyond the regime considered.

Plotting the LWEF at peak gain as function of carrier density in Fig.4, we note a drastic well width dependence. While the LWEF for the $10\,nm$ well increases monotonically, we see a clamping at a value of $\alpha \approx 3.0$ for the $3\,nm$ QW.

The clamping is partially due to the well-width dependence of the differential gain and refractive index discussed above. In addition, The smaller density of states and resulting stronger density dependence of the chemical potentials leads to the stronger blue shift of the peak gain in the narrower well. As can be seen in Fig. 1, this shift of the gain maximum in the narrow QW-structure significantly helps to obtain a clamping of the LWEF.

A monotonically increasing LWEF with carrier density has been previously observed experimentally in a similar structure as our $10\,nm$ well [8]. This data is included in Fig.2 for comparison. Experimental measurements of a narrow QW consisting of a $5\,nm$ $In_{0.14}Ga_{0.86}As$ QW in $150\,nm$ $Al_{0.2}Ga_{0.8}As$ barriers with $Al_{0.6}Ga_{0.4}As$

cladding layers are also shown in Fig.4. The experimental method of Ref. [8] was used to collect this data, although carrier densities in this work were extracted by comparing experimental gain spectra for given *current* densities to theoretical gain spectra at given *carrier* densities. This $5\,nm$ QW also exhibits a clamping of the LWEF to a value near $\alpha \approx 2.1$. The theoretical values are in good agreement with the experimental observation.

Against the general trend of decreasing LWEF with decreasing well width the α-values for the $5\,nm$ well are lower than those for the $3\,nm$ well. This is due to the specific energetic positions of the states in the different structures.

In summary, utilizing the delicate interplay between structure and gain material dependent carrier nonlinearities allows us to some degree to engineer the density dependence of the LWEF. In quantitative agreement with experimental results, our microscopic model calculations show that it is possible to design laser structures where the linewidth enhancement factor does not increase with increasing pump level, as in most common semiconductor laser configurations. Optimizing these features should make it possible to design more stable semiconductor lasers with spatially and spectrally stable modal properties, especially under high modulation rate or high power conditions.

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FIG. 1. Spectra of the LWEF for different carrier densities for the structures with a 3 nm QW (a) and 10 nm QW (b). The dots indicate the spectral position of the gain peak for the respective densities. For each structure, the sheet carrier densities are $5.0 \times 10^{12}\ 1/cm^2$, $4.0 \times 10^{12}\ 1/cm^2$, $3.0 \times 10^{12}\ 1/cm^2$, and $2.0 \times 10^{12}\ 1/cm^2$ (from top to bottom).

FIG. 2. Ratio of the carriers confined in the QW's, N_W/N, versus total density.

FIG. 3. Differential gain and differential refractive index as functions of carrier density. The applied density change is $0.05 \times 10^{12}\ 1/cm^2$.

FIG. 4. LWEF at peak gain as function of carrier density for different QW widths. The symbols are experimental results.

Fig. 1.

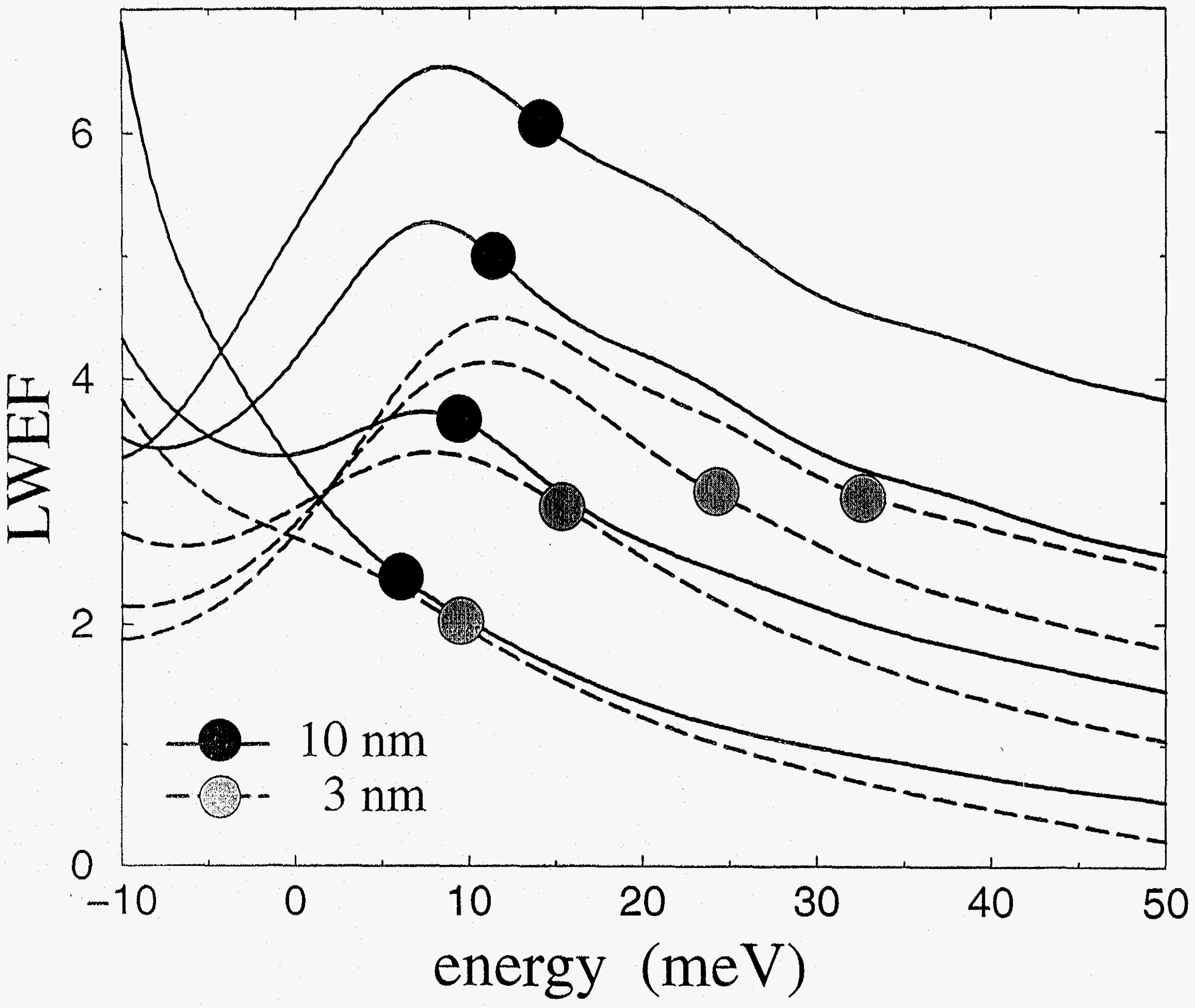


Fig. 2

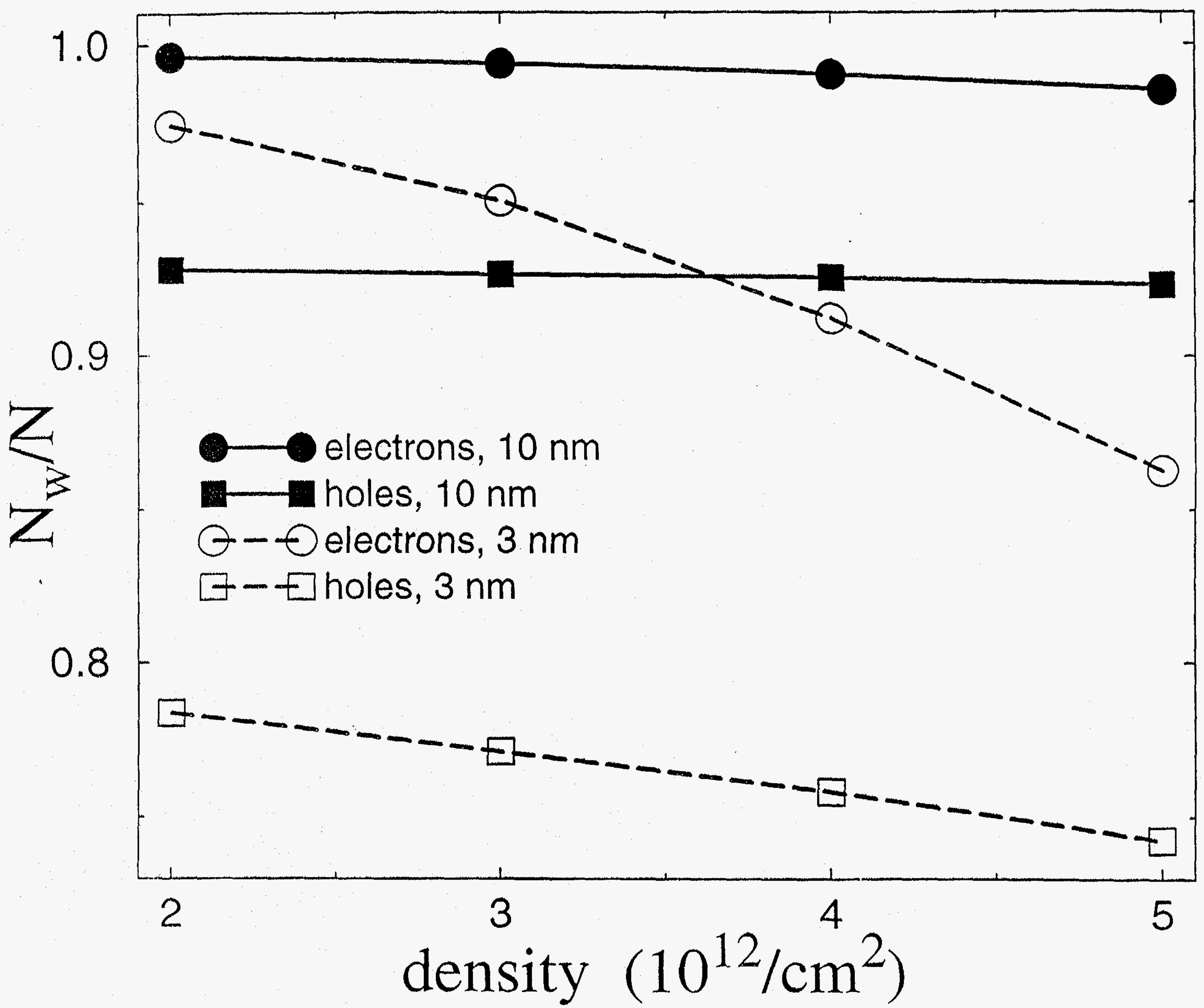
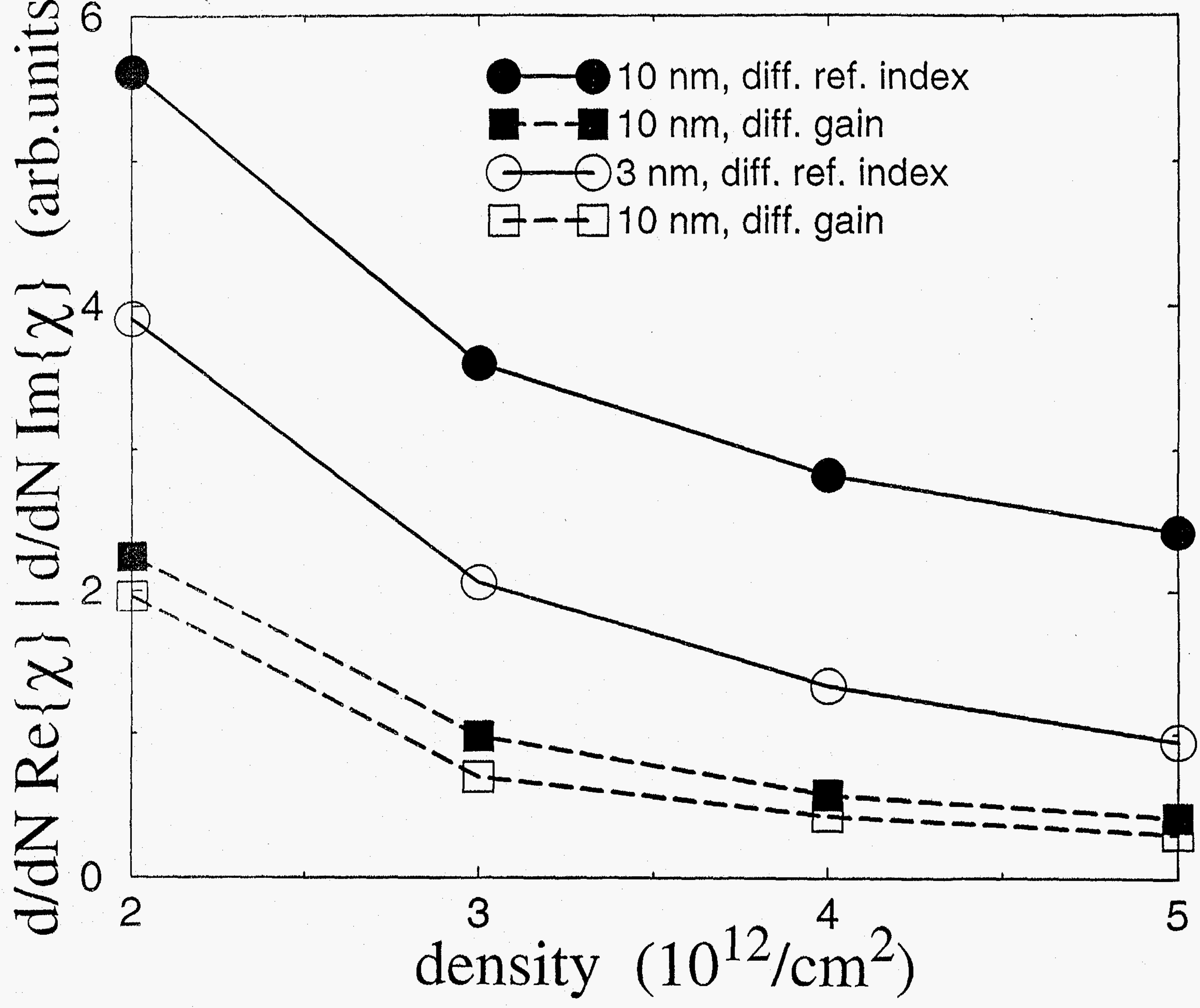
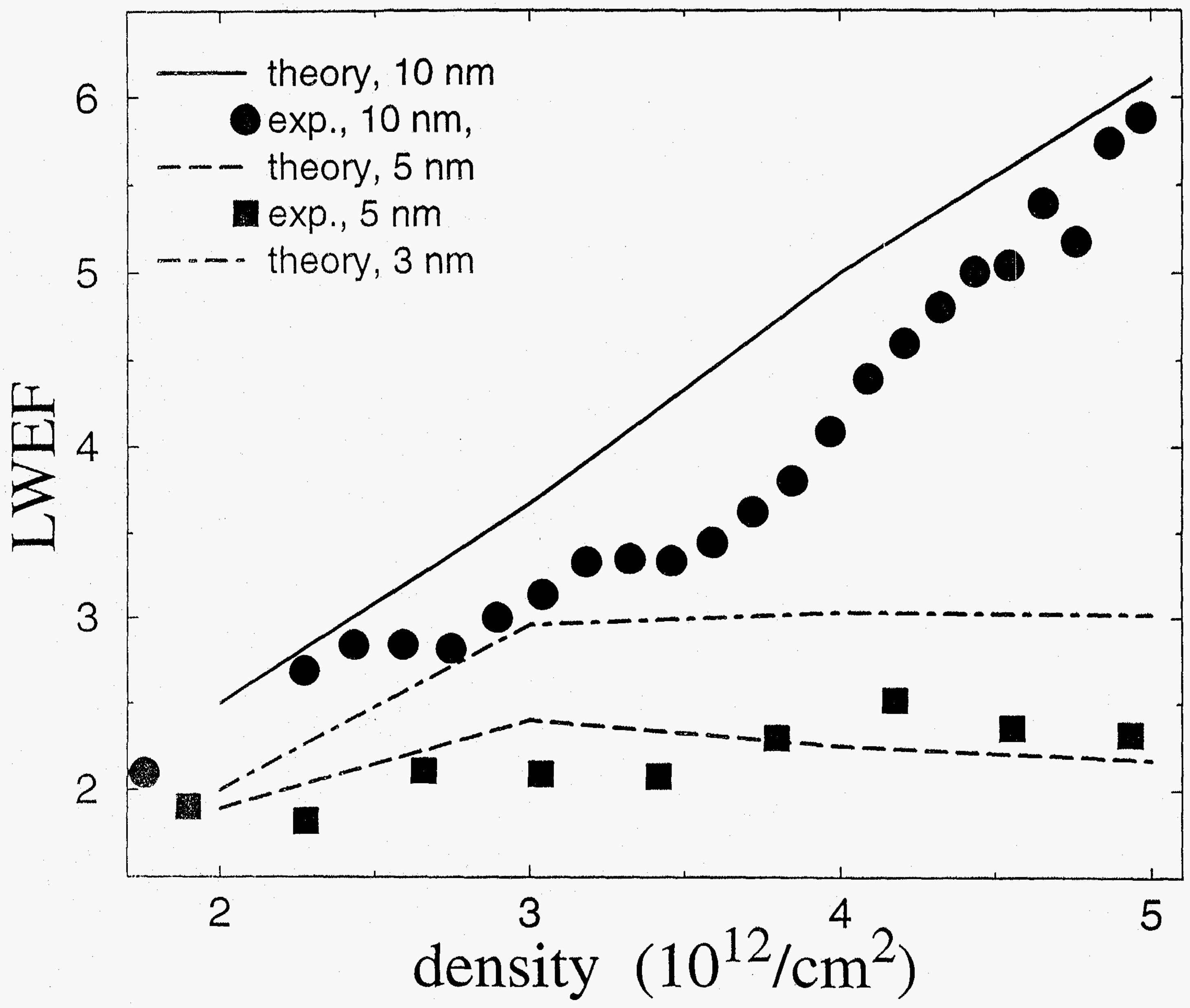

1.0
0.9
0.8
N_w/N
2
3
4
5
density $(10^{12}/\mathrm{cm}^2)$
electrons, 10 nm
holes, 10 nm
electrons, 3 nm
holes, 3 nm

Fig. 2



10 nm, diff. ref. index
10 nm, diff. gain
3 nm, diff. ref. index
10 nm, diff. gain
d/dN Re{χ} | d/dN Im{χ} (arb.units)
0
2
4
6
2
3
4
5
density ($10^{12}/cm^2$)

Fig. 4


theory, 10 nm
● exp., 10 nm,
theory, 5 nm
■ exp., 5 nm
theory, 3 nm
6
5
4
3
2
LWEF
2
3
4
5
density $(10^{12}/cm^2)$