threshold lasers are desired. The present experiments, i.e., the "ideal" form of I-V characteristics apparent in Fig. 2, show that implantation can be used to overcome this problem.

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[1]W. D. Laidig, N. Holonyak, Jr., M. D. Camras, K. Hess, J. J. Coleman, P. D. Dapkus, and J. Bardeen, Appl. Phys. Lett. **38**, 776 (1981).
[2]N. Holonyak, Jr., W. D. Laidig, M. D. Camras, J. J. Coleman, and P. D. Dapkus, Appl. Phys. Lett. **39**, 102 (1981).
[3]N. Holonyak, Jr. and W. D. Laidig, U. S. Patent No. 4 378 255 (29 March 1983) (filed May 6, 1981).
[4]K. Meehan, N. Holonyak, Jr., J. M. Brown, M. A. Nixon, P. Gavrilovic, and R. D. Burnham, Appl. Phys. Lett. **45**, 549 (1984).
[5]K. Meehan, P. Gavrilovic, N. Holonyak, Jr., R. D. Burnham, and R. L. Thornton, Appl. Phys. Lett. **46**, 75 (1985).
[6]K. Meehan, P. Gavrilovic, J. E. Epler, K. C. Hsieh, N. Holonyak, Jr., R. D. Burnham, R. L. Thornton, and W. Streifer, J. Appl. Phys. **57**, 5345 (1985).
[7]P. Gavrilovic, K. Meehan, J. E. Epler, N. Holonyak, Jr., R. D. Burnham, R. L. Thornton, and W. Streifer, Appl. Phys. Lett. **46**, 857 (1985).
[8]N. Holonyak, Jr., U. S. Patent No. 4 511 408 (16 April 1985) (filed April 22, 1982).
[9]J. J. Coleman, P. D. Dapkus, C. G. Kirkpatrick, M. D. Camras, and N. Holonyak, Jr., Appl. Phys. Lett. **40**, 904 (1982).
[10]M. D. Camras, J. J. Coleman, N. Holonyak, Jr., K. Hess, P. D. Dapkus, and C. G. Kirkpatrick, in *Proceedings of the International Symposium on GaAs and Related Compounds, Albuquerque, 1982,* edited by G. E. Stillman (Institute of Physics, London, 1983), pp. 232–239.
[11]P. Gavrilovic, D. G. Deppe, K. Meehan, N. Holonyak, Jr., J. J. Coleman, and R. D. Burnham, Appl. Phys. Lett. **47**, 130 (1985).
[12]R. D. Dupuis, L. A. Moudy, and P. D. Dapkus, in *Proceedings of the 7th International Symposium on GaAs and Related Compounds, St. Louis, 1978,* edited by C. M. Wolfe (Institute of Physics, London, 1979), pp. 1–9.
[13]R. W. Kaliski, P. Gavrilovic, K. Meehan, J. Gavrilovic, K. C. Hsieh, G. S. Jackson, N. Holonyak, Jr., J. J. Coleman, R. D. Burnham, R. L. Thornton, and T. L. Paoli, J. Appl. Phys. **58**, 101 (1985).

Fermi energy dependence of linewidth enhancement factor of GaAlAs buried heterostructure lasers

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The linewidth enhancement factor α is measured in a number of GaAlAs lasers with different internal losses. It is found that α decreases monotonically with the increase of the loss (Fermi energy level) in agreement with the theoretical prediction. On the basis of these results the design of cavity length and mirror reflection in order to reduce the spectral linewidth of the laser output is discussed.

The linewidth enhancement factor α[1,2] is of fundamental importance in semiconductor lasers (SCL's). It explains the anomalously large spectral linewidth of SCL's[1,2,3] and determines the amount of undesired frequency modulation (or chirp) accompanying the AM modulation of these lasers.[4] The measurement of the α parameter involves the AM to FM conversion in a modulated laser,[4] measuring the correlation between AM and FM noise in the SCL output, or other more indirect measurements.[5] Measured values of α range between 2.2 and 6. Part of this spread is due most likely to the fact that the measured lasers are of different types and the basic structure of some of these lasers involves a nonuniform carrier distribution which along with diffusion causes an increase of α. A second and more fundamental reason for the variation of the measured value of α is its dependence on the Fermi energy in the (pumped) semiconductor. This dependence follows directly from the definition of α in terms of the electron density (n) dependent electronic susceptibility $\chi(n)$ of a semiconductor[2]

$$\alpha = \frac{d\chi_R(n,E)/dn}{d\chi_I(n,E)/dn}, \tag{1}$$

where

$$\chi(n,E) \equiv \chi_R(n,E) + i\chi_I(n,E). \tag{2}$$

The imaginary and real parts of $\chi(n)$ are given by[6]

$$\chi_I(n,E) = \int B(\epsilon)\rho_{\rm red}(\epsilon)(f_c - f_v) \times \frac{(\hbar/\tau_{\rm in})}{(E-\epsilon)^2 + (\hbar/\tau_{\rm in})^2} d\epsilon, \tag{3}$$

$$\chi_R(n,E) = \int B(\epsilon)\rho_{\rm red}(\epsilon)(f_c - f_v) \times \frac{(E-\epsilon)}{(E-\epsilon)^2 + (\hbar/\tau_{\rm in})^2} d\epsilon - \frac{r_0 \hbar c^2 m_0}{2\pi E} \times \left(\frac{n}{m_c^*} + \frac{p}{m_v^*}\right), \tag{4}$$

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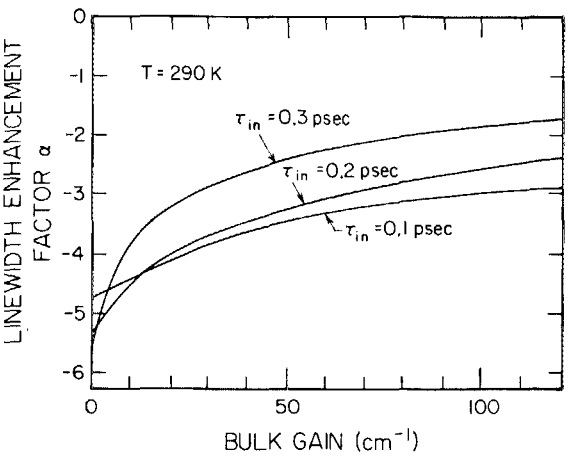

FIG. 1. Calculated α as a function of necessary total gain for lasing with various intraband relaxation times τ_{in}.

where E is the photon energy, ρ_{red} is the reduced density of states, τ_{in} is the intraband relaxation time, $f_c(f_v)$ is the Fermi–Dirac function of electrons (holes) with quasi-Ferm energy levels $E_{F_c}(E_{F_v})$, the $B(\epsilon)$ is a coefficient proportional to a square of the absolute value of the dipole matrix element, r_0 is the classical radius of the electron, n_0 is the refractive index, m_0 is the mass of electrons, $m_c^*(m_v^*)$ is the effective mass of electrons (holes), $n(p)$ is the carrier concentration of electrons (holes), c is the optical velocity, and $\hbar$ is the Planck's constant divided by 2π. The first term of Eq. (4) is the contribution to $\chi_R(n,E)$ due to band-to-band recombination while the second term is due to free-carrier absorption. It follows from (1), (3), and (4) that α depends on the Fermi energies E_{F_c} and E_{F_v}. These quasi-Fermi levels are determined by both the charge neutrality condition and the condition that the net modal gain is equal to the sum of the integral loss α_0 and the mirror loss $\ln(1/R)L$, where R and L are the mirror reflectivity and the cavity length, respectively. We thus expect that in a given laser α should depend strongly on the total loss.

Figure 1 shows a calculated plot of α at the photon energy corresponding to the maximum bulk gain g_{max}, as a function of g_{max}, for various intraband relaxation times ($\tau_{in} = 0.3, 0.2, 0.1$ ps). Note that higher values of losses hence of g_{max} lead to higher values of E_{F_c} and E_{F_v}. Since the active layer is undoped, the density of states is assumed to be parabolic. The absolute value of α at a given photon energy increases with the increase of the Fermi energy (carrier density). Figure 1 shows, however, that the absolute value of α at the photon energy of maximum gain, which is the quantity of interest, decreases with the increase of the Fermi energy. This suggests that the introduction of higher loss in a laser oscillator would lead to a smaller value of α. We also notice that the calculated change in α with the increase of g_{max} is bigger for larger assumed values of τ_{in}, especially in the region of low g_{max}. In the region of high g_{max}, on the other hand, α saturates to a value which is smaller for smaller τ_{in}. This is due to the fact that larger τ_{in} leads to less broadening of the gain profile and the change in α is more pronounced.

To check our theory we prepared six GaAlAs buried heterostructure lasers which are grown by liquid phase epitaxy (LPE). Samples #1–4 have a short (150 μm) cavity length, and the other lasers have long cavity length of 300 μm (samples #5, 6). All the lasers were fabricated from the same wafer. The measurement of the spontaneous emission spectrum revealed that the peak wavelength of the emission spectrum is almost the same in these lasers at low injection currents. This indicates that the band gap of these lasers can be taken to be the same; reflecting the fact that the aluminum content is almost uniform on the wafer region where these laser chips are taken. On the other hand, the lasing wavelengths of these lasers are different; the wavelengths of samples #1–6 are 8282 A, 8303 A, 8325 A, 8347 A, 8386 A, and 8397 A, respectively. Since the band gaps are the same in these lasers, the observed difference of the lasing wavelength indicates a different Fermi energy level (loss) at laser oscillation in each laser.

The α parameter of the six test lasers was measured using the AM to FM conversion method.[4] The SCL was biased above threshold and a small sinusoidally varying current at the frequency Ω was superimposed on the dc bias. Values of Ω exceeding 1 GHz were used to avoid spontaneous emission effects. If we assume a uniform carrier density and use a small modulation depth, then α is given by[4]

$$\alpha = -2\beta/m, \tag{5}$$

where m is the intensity modulation index and β is the phase modulation index which is obtained by solving the following equation:

$$\frac{S_1}{S_0} = \frac{J_1^2(\beta) + \{(m/4)[J_2(\beta) - J_0(\beta)]^2\}}{J_0^2(\beta) + (m/2)^2 J_1^2(\beta)}, \tag{6}$$

where S_1/S_0 is the relative sideband strength and $J_n(\beta)$ are nth order Bessel functions. Note that Eq. (6) is a corrected formula of Eqs. (9b) and (9c) in Ref. 4.

The intensity modulation index was measured with a *p-i-n* GaAs photodiode (ORTEL Corp.) whose output current was fed to the input of a microwave spectrum analyzer. The optical spectrum was measured with a confocal scanning Fabry–Perot resonator (Tropel 240) with an RCA 473 photomultiplier. The output of the photomultiplier was fed to a digital memory processor. Care was taken to avoid back reflection into the laser.

The measurement of α was performed varying m and Ω slightly and averaging the observed data. The standard deviations of the data are about 1 in all samples. Figure 2 shows the measured results of α as a function of lasing photon ener-

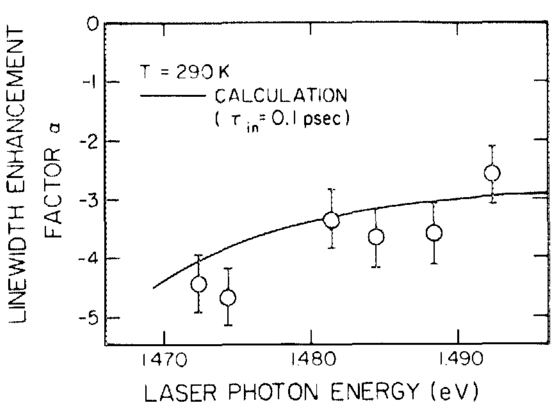

FIG. 2. Measured α as a function of lasing wavelength. The solid curve shows the calculated α with $\tau_{in} = 0.1$ ps.

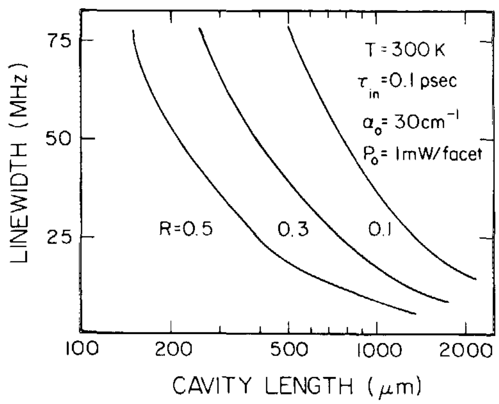

FIG. 3. The calculated linewidth as a function of cavity length L with various mirror reflection coefficients R.

gy together with calculated results for the intraband relaxation time $\tau_{in} = 0.1$ ps. In the calculation, the curve is fitted so that the calculated photon energy at which the gain is maximum coincides with the observed lasing wavelength. The measured result indicates that α decreases with the increase of the lasing photon energy (i.e., Fermi energy), as predicted by the theory. These results suggest that the divergence of measured α so far reported should be partly attributed to differences in the losses of the lasers measured.

We have demonstrated the Fermi energy dependence of α and indicated that the introduction of a high loss mechanism which causes the increase of the Fermi energy is effective in reducing α. However, this should not suggest that high losses are effective in reducing the laser linewidth $\Delta\nu$ since $\Delta\nu$ depends on other parameters such as the spontaneous emission factor, mirror loss, and total loss. It is given by[1]

$$\Delta\nu = \frac{v_g^2 h\nu(\Gamma g)[L^{-1}\ln(1/R)]n_{sp}}{8\pi P_0}(1+\alpha^2), \qquad (7)$$

where P_0 is the output power per facet, α is the noise enhancement factor, Γ is the optical confinement factor, v_g is the group velocity of light in the active layer, $h\nu$ is the photon energy, and n_{sp} is the spontaneous emission factor. Although the reduction of α contributes to the reduction of $\Delta\nu$, the high loss causes an increase of Γg and $[L^{-1}\ln(1/R)]$. On the other hand, n_{sp} decreases with the increase of losses (Fermi energy). Thus the change in the contribution of each parameter due to the increase of the Fermi energy is different, which makes it difficult to predict intuitively the dependence of $\Delta\nu$ on the Fermi energy level. In order to clarify the loss dependence, we plot in Fig. 3 the calculated laser linewidth $\Delta\nu$ as a function of cavity length L with various mirror reflection coefficients R. Note that each combination of $\{L,R\}$ leads to a different E_{F_c}. In this calculation τ_{in} is assumed to be 0.1 ps and internal loss in the active layer is assumed to be 30 cm^{-1}. The result indicates that $\Delta\nu$ is reduced by increasing R and L, although this reduces the loss which leads to the enhancement of $(1+\alpha^2)$. This indicates that $\Delta\nu$ is determined mainly by the internal loss Γg and mirror loss $L^{-1}\ln(1/R)$ in Eq. (7) and also that the reduction of α due to the increase of the Fermi energy is more than offset by the increase in these factors. The result that larger values of L and R contribute to a reduction of $\Delta\nu$ is applicable not only to the Fabry–Perot type laser but also to the distributed feedback laser (DFB) even if we consider the dependence of α and n_{sp} on the Fermi energy levels. In the case of a DFB laser the increase of R corresponds to the increase of the coupling coefficients κ.

In conclusion, we measured the linewidth enhancement factor α of GaAlAs buried heterostructure lasers with different losses at room temperature and demonstrated the dependence of α on the Fermi energy levels at laser oscillation. The results indicate that the absolute value of α decreases with the increase of the Fermi energy levels, as predicted by theory. These results suggest that the divergence of the measured α is partly attributed to the variation of the Fermi energy level in different lasers. Furthermore, we indicate that the introduction of high mirror reflectivities and long cavity lengths is effective for reducing the spectral linewidth.

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[1]C. H. Henry, IEEE J. Quantum Electron. **QE-18**, 259 (1982).
[2]K. Vahala and A. Yariv, IEEE J. Quantum Electron. **QE-19**, 1102 (1983).
[3]M. W. Fleming and A. Mooradian, Appl. Phys. Lett. **38**, 511 (1981).
[4]C. Harder, K. Vahala, and A. Yariv, Appl. Phys. Lett. **42**, 328 (1983).
[5]K. Kikuchi and T. Okoshi, Electron. Lett. **44**, 32 (1984).
[6]K. Vahala, L. C. Chiu, S. Margalit, and A. Yariv, Appl. Phys. Lett. **42**, 631 (1983).