Optical measurement of ion implantation damage depth in multiple-quantum-well mesa structures

M. Lynch and J. Hegarty
Optronics Ireland Research Centre, Department of Pure and Applied Physics, Trinity College, Dublin 2, Ireland

A. Ginty and W. M. Kelly
Optronics Ireland, National Microelectronics Research Centre, University College, Lee Maltings, Prospect Row, Cork, Ireland

W. T. Tsang
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 25 April 1991; accepted for publication 3 June 1991)

We have determined the depth of ion implant damage in semiconductor materials by nonlinear optical measurements. The carrier lifetime in ion-implanted mesas was measured by the pump-probe technique, and the carrier diffusion coefficient in unetched material was measured by degenerate four-wave mixing. An effective depth of damage within which the carriers experience fast recombination is then determined by modeling of the carrier dynamics in the mesa structure.

Ion implantation is one of the basic techniques used to process semiconductors, and several methods exist to characterize the range statistics of implanted ions in a host semiconductor.[1] Ion-induced damage has also been used to modify the optical properties of semiconductors[2] where the carrier lifetime is reduced due to enhanced carrier recombination at damage sites. However, since the relationship between ion dose and damage is nonlinear[3] and since the penetration depth depends on many factors such as material composition and crystal orientation, there is no simple relationship between the energies and dose of implanted ions and the depth at which there is sufficient damage to cause fast recombination. This discrepancy is particularly acute for large ion doses since there will be significant ion penetration beyond the mean position, and therefore the shape of the distribution and not just the mean range must be known to estimate this depth. There is need of a technique to characterize the depth of the damage produced by ion implantation rather than the depth of ion penetration. Wong *et al.*[4] have used a method of using quantum wells of different thicknesses at increasing depths acting as markers to investigate the depth of damage caused by reactive-ion etching, but this method is limited in the depth obtainable by the overall thickness of the epitaxial layer.

The method we describe in this letter for measuring this depth consists of implanting the sides of a multiple-quantum-well (MQW) mesa and optically measuring the carrier decay using a pump-probe technique. We then model the implanted mesa as an unimplanted region which exhibits slow intrinsic carrier decay and from which the pump-probe signal is obtained, surrounded by the implanted region with no observable pump-probe signal and very fast carrier recombination. This is depicted in Fig. 1, where z is the depth to which this fast recombination occurs which gives an effective radius $R_{\mathrm{eff}} = R - z$ for the carriers in the unimplanted region. The carrier decay is governed by the diffusion of carriers from the unimplanted region and recombination at damage sites in the outer region. By modeling the response using an optically measured value for the carrier diffusion coefficient, the depth of the ion implant damage can be determined.

The MQW sample used consisted of 70 periods of 150-Å InGaAs wells and 100-Å InP barriers grown by chemical-beam epitaxy.[5] The heavy-hole exciton resonance was centered at 16 μm at room temperature. The electron-beam resist (0.5-μm-thick poly-ethyl-cyano-acrylate) was vapor deposited and exposed using electron-beam lithography. Etching was carried out in a Plasma Technology 80S etcher using a methane-hydrogen mixture in a 1:10 ratio. An etch rate of approximately 0.02 μm/min was obtained with a total chamber pressure of 6×10^{-2} Torr, 100 W power, 320 V dc bias, and a temperature of 11 °C. Using this method, an array of 1.9-μm-diam mesas was produced. The sides of the mesas were then ion implanted with 100-keV As ions. The sample was tilted at 45° to the incoming ion beam to maximize the exposure of the sidewalls of the mesas, and four implants were performed with the sample rotated through 90° in the plane of the wells between each

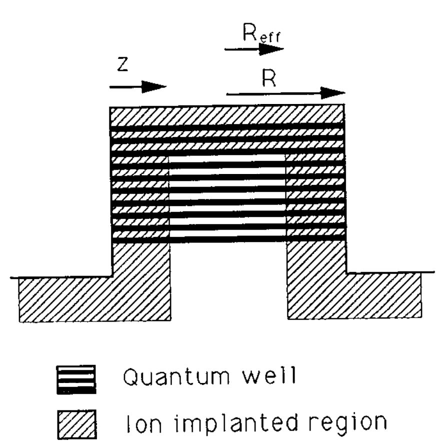

FIG. 1. Schematic diagram (not to scale) of the model for the ion-implanted MWQ mesa.

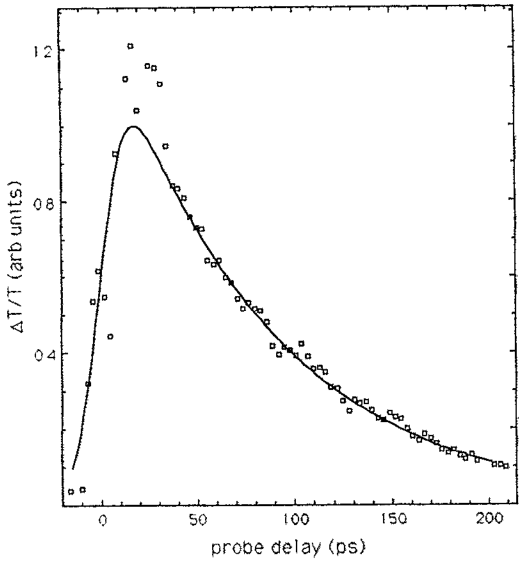

FIG. 2. Decay of measured $\Delta T/T$ signal in arbitrary units (circles) and fit obtained from model (solid line) for MQW mesa structure.

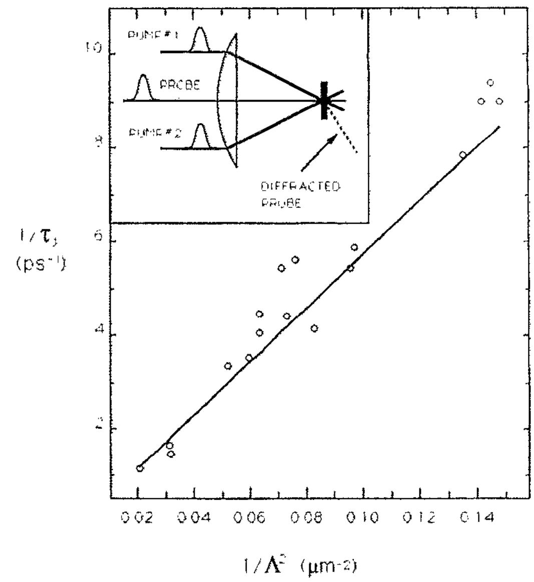

FIG. 3. DFWM decay rate as a function of the inverse square of the grating spacing. The circles are the experimental values and the solid line is the best fit obtained for $D = 7.3$ cm^2/s. The inset shows the beam configuration for the DFWM measurements.

exposure. Each dose was 10^{16} cm^{-2} at a beam current of 100 μA.

Optical characterization was carried out with a mode-locked NaCl:OH color center laser which provided 15 ps pulses at a 100 MHz repetition rate tuned to the heavy-hole exciton resonance at 1.6 μm. To measure the carrier lifetime, the laser output was split to provide pump and probe beams. The probe beam was passed through a stepper motor-controlled delay line, attenuated and recombined collinearly with the orthogonally polarized pump. The pump was chopped at 80 Hz and the probe at 1800 Hz. The two beams were then coupled through a short length of single-mode silica fiber which ensured good beam overlap, independent of any delay-line misalignment.[6] The fiber output was collimated and focused to a 2.5-μm spot with a 40× microscope objective. A single mesa was positioned in the focal spot using a piezoelectric micropositioning stage, and a polarizer and photodiode were used to detect the transmitted probe beam. The nonlinear transmission $\Delta T/T$ was measured by the conventional double lock-in technique, where T is the transmission and ΔT the change in transmission of the probe beam caused by the pump beam. The time-resolved carrier density is obtained by measuring $\Delta T/T$ as a function of probe delay. The measured response (Fig. 2) of the implanted mesa has an exponential decay time of 70 ps, compared with 5 ns before implantation and an intrinsic carrier lifetime of 35 ns. This intrinsic lifetime was measured in an unetched piece of the same MQW material using a similar pump-probe technique but with a much larger focal spot size to reduce the effects of carrier diffusion. This measurement was repeated after implantation on unetched material adjacent to the mesa array and no change in the carrier lifetime was observed. This implies that we need not consider implantation through the top surface of the mesa, which is an important point since our results show that there is significant penetration of ions through the top of the mesa into the MQW. Also, since the response of the unimplanted mesas is almost two orders of magnitude slower than after implantation, we can also neglect the effects of damage due to the reactive-ion etching. Our assumption that the carrier decay for the implanted mesa is determined by diffusion to and recombination in the ion-implanted region is therefore justified.

The ambipolar diffusion coefficient was measured using degenerate four-wave mixing (DFWM)[7] in an unetched piece of the same MQW sample as follows. The laser output was split to provide two pump beams and a probe beam. The two pump beams were adjusted to equal delay and intensity, chopped at approximately 80 Hz and focused onto the sample (see inset of Fig. 3) together with the attenuated probe beam which was chopped at a higher frequency (1800 Hz). The diffracted probe signal was detected with a germanium photodiode and two lock-in amplifiers in series. The decay time τ_d of the transient grating produced by the pump beams can be measured from the decay of the diffracted probe beam as the probe delay is increased. Measurements of τ_d were performed for a range of angles between the pump beams of 13° and 35°, giving a range of grating spacing from 7 to 2.5 μm. Corrections were made for the scatter of the pump-probe signal onto the detector. The grating decay time τ_d is related to the grating spacing Λ by the equation[8]

$$\tau_d^{-1} = (8\pi^2 D/\Lambda^2) + 2\tau_L^{-1}$$

with

$$\Lambda = \lambda/2\sin(\theta/2), \qquad (1)$$

where D is the diffusion coefficient, θ the angle between the probe beams, λ the laser wavelength, and τ_L the intrinsic carrier lifetime (35 ns). The experimental data is shown in Fig. 3 as $1/\tau_d$ vs $1/\Lambda^2$ with the best-fit line giving D as 7.3 cm^2/s with a standard deviation of 4%.

To model the nonlinear response of the mesa, we define R as the mesa radius and assume that the ion implantation produces a region to a depth z in the sample where the carrier recombination is instantaneous compared to the response time of the mesa and where no nonlinear response is obtained. This can be justified since the ion dose used is sufficient to produce an amorphous region in the material[2] within the penetration depth of the ions, and so we can define this effective depth z to be the region where the carriers see sufficient damage to cause fast recombination. This gives an effective radius of $R_{eff} = R - z$, where R is the actual mesa radius. The carrier density $n(r,t)$ as a function of time t and distance from the mesa center r obeys the two-dimensional diffusion equation[9]

$$\frac{\partial n}{\partial t} = D\nabla^2 n - \frac{D}{\tau_L}, \qquad (2)$$

a solution for which for the cylindrical geometry of the mesa is[10]

$$n(r,t) = e^{-\psi_i t} J_0(x_i r/R_{eff}), \qquad (3)$$

where ψ_i is the decay rate given by

$$\Psi_i = \tau_L^{-1} + (Dx_i^2/R_{eff}^2). \qquad (4)$$

The x_i values are solutions of $J_0(x) = 0$, equivalent to setting the carrier density to zero at the boundary of the damaged region. The particular solution is then given by a sum of eigenfunctions:

$$n(r,t) = \sum_{i=1}^{\infty} A_i e^{-\psi_i t} J_0\left(\frac{x_i r}{R_{eff}}\right), \qquad (5)$$

The A_i coefficients are obtained from the initial carrier density $n(r,t=0)$, which is proportional to the intensity profile of the laser spot. The nonlinear response can then be calculated from the product of the carrier density and the initial carrier density, i.e.,

$$\frac{\Delta T}{T}(t) = k \int_0^{R_{eff}} n(r,t) n(r,t=0) dr, \qquad (6)$$

where k is a constant of proportionality. This response is then convoluted with the pump and probe pulse shapes to allow easier fitting to the measured response. By varying R_{eff} and k and finding the best fit to the measured response of the mesa, the implant depth z can be determined. Figure 2 shows the measured response of the mesa with the best fit obtained for $R_{eff} = 0.56$ μm, giving an implant depth of 0.4 μm. The region around zero delay where the pump and probe pulses overlap temporally was not used for fitting as the data was not considered reliable because of coherence effects and possible nonlinearity in the optical fiber.

This technique can be easily extended to different ions and energies. For shallower depths, smaller mesas could be used. For deeper implants, as well using larger mesas, wider spacing of the mesas would allow nearer to normal incidence to the sidewalls of the ion beam, thus reducing penetration of the ions into the top of the mesa. Alternatively, the mesas could be implanted before removal of the mask used for the etching process.

This work was supported through the European Community Science Programme, contract No. SC10172C(EDB).

[1] J. F. Ziegler, Ed., *Ion Implantation Science and Technology* (Academic, San Diego, 1988).
[2] Y. Silberberg, P. W. Smith, D. A. B. Miller, B. Tell, A. C. Gossard, and W. Weigman, Appl. Phys. Lett. **46**, 701 (1985).
[3] S. M. Gulwadi, M. V. Rao, D. S. Simons, O. W. Holland, W.-P. Hong, C. Caneau, and H. B. Deitrich, J. Appl. Phys. **69**, 162 (1991).
[4] H. F. Wong, D. L. Green, T. Y. Liu, D. G. Lishan, M. Bellis, E. L. Hu, P. M. Petroff, P. O. Holtz, and J. L. Merz, J. Vac. Sci. Technol. **6**, 1906 (1988).
[5] W. T. Tsang, Appl. Phys. Lett. **45**, 1234 (1984).
[6] K. Tai, S. L. McCall, and W. T. Tsang, Appl. Phys. Lett. **53**, 737 (1988).
[7] J. Hegarty, M. D. Sturge, A. C. Gossard, and W. Weigmann, Appl. Phys. Lett. **40**, 132 (1982).
[8] J. R. Salcedo, A. E. Seigman, D. D. Dlott, and M. D. Fayer, Phys. Rev. Lett. **41**, 131 (1978).
[9] M. Ali Omar, *Elementary Solid State Physics* (Addison-Wesley, Reading, MA, 1975).
[10] K. Tai, T. R. Hayes, S. L. McCall, and W. T. Tsang, Appl. Phys. Lett. **53**, 302 (1988).