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Effects of heavy-ion and light-ion irradiation on the room temperature carrier dynamics of InGaAs/GaAs quantum wells

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Abstract

The effects of irradiation by $^{59}Ni^+$, $^{20}Ne^+$, $^4He^+$ and $^1H^+$ ions on the carrier dynamics of InGaAs/GaAs quantum well heterostructures were studied using a femtosecond time-resolved up-conversion photoluminescence method. The carrier capture time for the light ions He^+ and H^+ was found to be almost independent of the irradiation dose, while for the irradiation with heavy ions Ni^+ and Ne^+ it decreases with the dose. The most efficient carrier collection into the quantum wells was observed for the Ne^+-irradiated sample, with a shortest capture time of about 1 ps. The heavy-ion-irradiated samples exhibited the shortest decay times (lifetime of carriers), which were 0.54 ps for Ne^+ and 0.62 ps for Ni^+. Irradiation by light ions He^+ and H^+ was as effective as with the heavy ions in achieving the desired short lifetimes, but for similar nuclear energy deposition and penetration depth for each ion species in the sample, much higher ion doses needed to be applied for lighter ions than did Ne^+ or Ni^+ to yield the same carrier lifetime. When comparing the results of irradiation for the Ne^+-irradiated sample with those of the Ni^+-irradiated one, we conclude that although the carrier lifetime and ion doses were about the same for both the methods, the $^{20}Ne^+$ ions are preferred over $^{59}Ni^+$ due to the faster carrier capture dynamics and remarkably lower implantation energy (0.4 MeV versus 10 MeV) needed to obtain the desired irradiation induced effects.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ion implantation is widely used for improving the carrier dynamics in III–V compound semiconductor heterostructures. One of the most studied heterostructures is InGaAs/GaAs quantum wells (QWs), which are employed as active regions of ultra-fast optoelectronic devices [1–3]. The carrier capture time and the carrier relaxation time are among the main parameters that determine the dynamic performance of the devices. Both heavy-ion irradiation and light-ion irradiation shorten the carrier lifetimes, but the resultant defect morphology is quite different. Heavy ions predominantly

create clusters of point defects, while light ions produce isolated point defects [4–9]. The defect morphology is expected to affect the dynamics of the free carrier capture by the defect levels and the carrier recombination. The defects with higher activation energies induced by heavy ions are considered to be more efficient and thermally stable than those created by light ions [4]. In [10] it is suggested, however, that irradiating multiple-quantum wells with light ions is as effective as using heavy ions when fabricating ultrafast saturable absorber devices. This is an interesting observation and deserves further studies from the point of view of the carrier dynamics resulted in, when the QW samples are irradiated by different light and heavy ions.

In the present work we perform a comparative study on irradiation of InGaAs/GaAs MQWs by heavy ions and light ions and investigate the effects of irradiation on carrier capture time and decay time using the time-resolved up-conversion technique and computer simulations. The criterion for comparison among the different light and heavy-ions was chosen such that each ion-irradiation produced the same amount of damage and penetration depth in the sample.

2. Experimental methods

The samples were grown by molecular beam epitaxy. They consisted of five compressively strained QWs made of 6 nm thick $In_{0.29}Ga_{0.71}As$/17-nm GaAs heterostructures deposited onto a 200 nm GaAs buffer layer on a GaAs (0 0 1) substrate and capped with a thin GaAs layer. The samples were irradiated by Ni^+ and Ne^+ (heavy ions) and He^+ and H^+ (light ions) at various doses and implantation energies, which were 10 MeV for Ni^+, 0.4 MeV for Ne^+, 0.2 MeV for He^+ and 0.1 MeV for H^+. A 5 MV EGP-10-II tandem accelerator was used for the Ni^+ irradiation and a 500 kV HVEC implanter for Ne^+, He^+ and H^+. Photoluminescence from these samples appeared at a wavelength of 1090 nm.

Time-resolved photoluminescence (TRPL) was measured using the femtosecond up-conversion method, as described elsewhere [11]. A femtosecond self-mode-locked titanium sapphire laser, pumped with an argon ion laser, was employed as a source of excitation pulses. The pulses had a wavelength of 820 nm, a pulse width of 50 fs, a repetition rate of 90 MHz, a time resolution of 100 fs, and an excitation power of 20–30 mW. The optical energy density on the sample surface was 0.3 mJ cm^{-2}.

3. Results and discussion

Each intense 820 nm excitation pulse having the density of carriers at the sample surface 10^{19} cm^{-2} injects free carriers high into the bands of quantum wells and barriers, creating a hot carrier distribution near the band edge. Since the barrier widths exceed the width of QWs by a factor of about 10, and the absorption coefficients in the barrier and in the QW are nearly equal, we may assume that most of the efficient carriers reaching the QWs are generated in the barriers. Those photo-excited carriers, which are generated elsewhere in the heterostructures and are not able to reach the quantum wells, would have no significance on the QWs PL dynamics. Furthermore, thermalization of these hot carriers

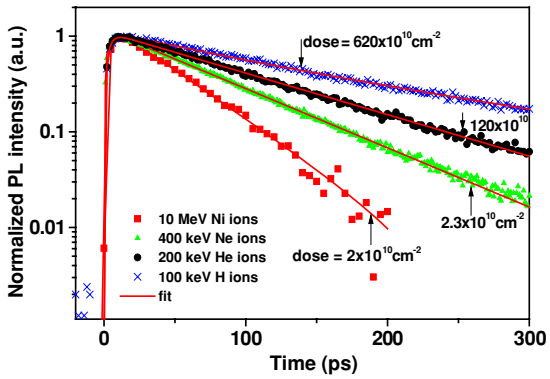

Figure 1. Selective TRPL decay profiles of InGaAs/GaAs QWs irradiated with Ni^+, Ne^+, He^+ and H^+ ions at different doses.

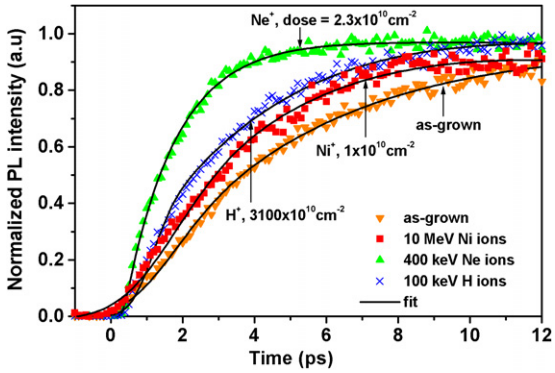

Figure 2. Time evolution (rise) of the PL signal from the as-grown sample ($\tau_{dec.} = 455$ ps) and the samples irradiated by different ions, but each with the same lifetimes of about 70 ps. The PL rise profile corresponding to He^+ was similar to that of H^+ and is not shown here for clarity. Among the different ions with similar decay times, the fastest capture dynamics can be seen for the Ne^+ ion.

occurs extremely fast [12,13] and will not affect carrier lifetime measurements. Upon ultra-fast thermalization, the carrier transfer from the GaAs barriers into the QWs can be divided in two time-sequential processes: (i) carrier transport and (ii) carrier capture. In the first step, free carriers diffuse from the barrier layers to the QWs; in the second step, the carriers are captured by the QWs via a scattering process from the unbound three-dimensional into the quasi-two-dimensional states of the QWs. If the barrier layer is not too thick (< 20 nm), and less than the carrier mean-free path (as in our case), then the transfer process is dominated by the carrier capture rate, whereas the carrier transport process (diffusion) can be neglected [12, 14–16].

The key parameters in photoluminescence are the rise time and the decay time. The rise time is defined as the time required for photoluminescence to reach its maximum, and depends upon carrier thermalization, carrier diffusion in the barriers, carrier capture into the QWs. As mentioned previously, in our case, the terms due to the carrier thermalization and the diffusion can be neglected. Therefore, the rise time is essentially due to a carrier capture rate by the QW.

Figure 1 illustrates TRPL decay profiles for the InGaAs/GaAs QWs upon irradiation by the heavy and light ions. Figure 2 shows details of the onset of TRPL (i.e., the

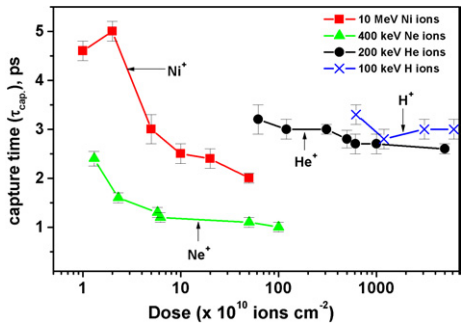

Figure 3. Carrier capture time ($\tau_{cap.}$) for different light and heavy ions as a function of irradiation dose. The capture time (not shown here) for the as-grown sample was 6 ps. The carrier capture time is almost independent of the dose for the light ions He^+ and H^+.

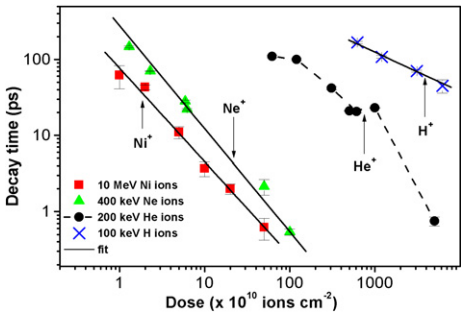

Figure 4. Decay time as a function of irradiation dose for different light and heavy ions. The desired decay time decrease is obtained with all the ions, but for Ni^+ and Ne^+ a much lower number of incident ions are needed to create the same decay time effect than for H^+ and He^+.

rise time) for as-grown and different ions with comparable lifetimes. Because the carrier rise and decay profiles depend exponentially on time t, photoluminescence intensity (I_{PL}) can be described approximately by

$$I_{PL}(t) = -a_1 \exp(-t/\tau_{cap}) + a_2 \exp(-t/\tau_{dec}).$$

We used a single exponential factor to fit the capture of the carriers with a characteristic time τ_{cap} and a single exponential factor τ_{dec} to describe the effective lifetime; a_1 and a_2 are pre-exponential factors.

Carriers from the barrier layer and the QW recombine in a non-radiative or radiative manner. Non-radiative recombination, which occurs via carrier capture by the defects, dominates the recombination mechanism at room temperature [17]. Therefore, the carrier lifetime extracted from the up-conversion TRPL data at room temperature is essentially determined by non-radiative recombination. The relaxation and capture of holes are known to be much faster than those of electrons; therefore, the decay and capture times recorded in our measurements are attributable to those of electrons [13, 18].

The observed exponential nature of QWs PL formation for as-grown and different heavy and light ions seen in figure 2 suggests that the time limiting step in filling the QWs states in not diffusion, but quantum carrier capture. This would mean that the carriers involved in the QWs PL emission are generated relatively near the QWs. For each ion species, the capture time (τ_{cap}) at different irradiation doses is presented in figure 3. As can be seen, the fastest capture process occurs for the Ne^+-irradiated sample with τ_{cap} between 1 and 2.4 ps at the doses shown in figure 3. It appears that while τ_{cap} is almost independent of the He^+ and H^+ doses it decreases with the Ni^+ and Ne^+ doses. For the as-grown samples (no irradiation), τ_{cap} was 6 ps. For the He^+ and H^+ irradiated samples, the average τ_{cap} was 3 ps and, for the Ni^+ sample, it varies between 2–5 ps depending on the dose. These time differences are small but discernable in TRPL with error limits $|\Delta\tau_{cap}| \leqslant 0.2$ ps. Thus, for irradiation with different light and heavy ions, relatively short capture time values were observed as compared to the capture time (6 ps) of the as-grown sample. Among all the ion species used in this work, the most efficient carrier collection into the QW was observed with Ne^+ ion irradiation with a shortest capture time of 1 ps. The effect of ion irradiation on the capture time can be understood in terms of the amount of defects incorporated and also on the kind of defects created by different ions. The fact that irradiation by He^+ and H^+ has little effect on τ_{cap} indicates that the defect morphology (point defects or complex defects) created at the QW interfaces is different for heavy ions and light ions. It is likely that the variation in τ_{cap} with irradiation dose for Ne^+ and Ni^+ is due to a creation of additional vacancies/defects at the QW interfaces, which may provide an additional carrier drift because of a concentration gradient present. Therefore, the carrier capture time depends not only on the amount of defects inside the heterostructures but also on the kind of defects each ion species creates. However, the effects created by the irradiation with different ions on the capture time of the QWs remain complex in nature and depends upon the defect dynamics. Other suitable experimental techniques and theoretical work are required to probe the defect dynamics in detail and are a topic of further investigation.

The amount of defects incorporated into the samples depends upon ion mass, implantation energy and irradiation dose. According to figure 1, the Ni^+-irradiated sample at the lowest ion dose exhibited the shortest TRPL decay profile, τ_{dec}, while the H^+-irradiated sample at a 600 times higher dose had the longest τ_{dec}. Figure 4 shows τ_{dec} in greater detail. We can see that τ_{dec} is inversely proportional to the ion dose. Compared to the as-grown sample (which had $\tau_{dec} \approx 460$ ps), the Ni^+-irradiated sample exhibited τ_{dec} from 62 ps to 0.62 ps in the dose range of (1–50) $\times 10^{10}$ ions cm^{-2}, and the Ne^+ sample had τ_{dec} from 147 ps to 0.54 ps in the range of (1.3–100) $\times 10^{10}$ ions cm^{-2}. Accordingly, lifetime shortening by Ni^+ and Ne^+ irradiation is very significant. For light ions, the shortest decay time of 0.75 ps was observed for the He^+-irradiation at dose 5×10^{13} ions cm^{-2}. Though all the ions shorten the lifetime, Ni^+ and Ne^+ do so at low ion doses. A comparison of Ni^+ with Ne^+ reveals that Ne^+ requires an implantation energy, which is 25 times smaller than that for Ni^+ to yield the same τ_{dec} value. In addition, Ni^+ and Ne^+ as heavy ions are believed to produce clusters of point defects, which are more stable than isolated point defects mainly produced by light ions [4–9]. Also, unlike the Ni ions, Ne being a noble gas it is easier to use in ion sources and can be used in smaller accelerator, which is much more suitable for irradiations. Thus, from the point of view stable

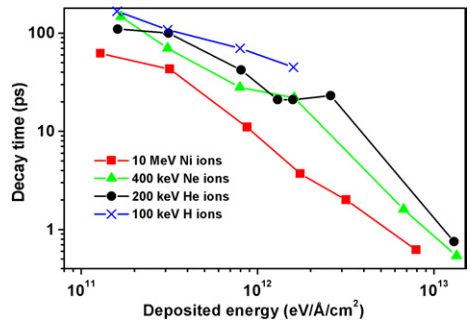

Figure 5. Decay time as a function of deposited energy for different light and heavy ions. The implantation energy for each ion is chosen such that similar penetration depth and deposited energy profiles are obtained. The nuclear deposited energies per ion are 1.2, 60 and 620 times smaller for Ne^+, He^+ and H^+ compared to Ni^+.

cluster defects (being heavy ion), less implantation energy requirement and faster carrier capture dynamics; the Ne^+ ion irradiation is preferred over the Ni^+ ion and other light ions. However, at an appropriate irradiation dose, each ion species used in this work seems to be equally effective in achieving the desired short decay time.

When calculating the capture and decay times, an important factor is the band filling of the quantum-confined energy levels in the QW at high excitation. As a result of band filling different carrier dynamics would be observed. In order to ensure that there was no band filling effect in our experiments, we made measurements at different excitation intensities. We found that the measured photoluminescence rise and decay times did not depend on excitation intensity.

Ni^+, Ne^+, He^+ and H^+ have different masses, and depending on their implantation energies, they deposit different amounts of energy into the sample. The implantation energies were chosen in such a way that the penetration depth and energy deposition for all ions are similar. For each ion the mean penetration depth is much larger ($>$ 500 nm) than the active region (but it should be noted that the energy deposited to nuclear collisions in the bulk differs from that in the near-surface region having the active region [19]). The deposited nuclear energies were calculated using a SRIM2003 computer code [20]. Figure 5 shows the measured carrier lifetimes as a function of simulated deposited energies. At similar depth and energy deposition profiles a dramatic difference in the decay time with nuclear deposited energy is seen in figure 5. At the implantation energies used here, damage is produced almost solely by nuclear energy deposition. Moreover, the ion energies are high enough that they stop much deeper than in active layers. Hence, the fact that even after normalization with the damage energy there are big differences between the ions shows that the effect on decay time is dependent not only on the total amount of damage, but also on what kind of damage (creation of point defects or complex defects) each ion produces. The calculations point out that the deposited energies per ion are 1.2, 60 and 620 times smaller for Ne^+, He^+ and H^+ than for Ni^+, respectively. This explains why much larger doses are needed for He^+ and H^+ to obtain comparable effects on τ_{dec} (figure 4), while Ne^+ and Ni^+ are similar to each other in this respect.

4. Conclusion

The effects of ion irradiation on the dynamic properties of InGaAs/GaAs quantum wells were studied using heavy ions (Ni^+, Ne^+) and light ions (He^+, H^+) for irradiation at the ion energies of 10, 0.4, 0.2 and 0.1 MeV, respectively, by applying a femtosecond time-resolved up-conversion technique. The carrier lifetime in the QW decreased as the irradiation dose and the deposited nuclear energy were increased. The fastest carrier capture and decay times were observed for Ne^+ irradiated samples at the doses comparable to those used for the Ni^+ samples. Although the light ions are effective in achieving the short lifetimes, yet they did not appear to be effective generators of crystal defects at reasonable dose levels. It was concluded that Ne^+ is an appropriate alternative to the Ni^+ irradiation for controlled creation of defects in GaInAs/GaAs quantum well heterostructures for ultra-fast optoelectronic devices.

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References

[1] Singh J 1995 *Semiconductor Optoelectronic: Physics and Technology* (New York: McGraw-Hill)
[2] Okhotnikov O, Grudinin A and Pessa M 2004 *New J. Phys.* **6** 1
[3] Hakkarainen T, Pavelescu E-M, Arstila K, Dhaka V D S, Hakulinen T, Herda R, Konttinen J, Tkachenko N V, Lemmetyinen H, Keinonen J and Pessa M 2005 *J. Phys. D: Appl. Phys.* **38** 985
[4] Joulaud L, Mangeney J, Lourtioz J-M, Crozat P and Patriarche G 2003 *Appl. Phys. Lett.* **82** 856
[5] Mangeney J, Stelmakh N, Aniel F, Boucaud P and Lourtioz J-M 2002 *Appl. Phys. Lett.* **80** 4711
[6] Mangeney J, Lopez J, Stelmakh N, Lourtioz J-M, Oudar J-L and Bernas H 2000 *Appl. Phys. Lett.* **76** 40
[7] Nordlund K, Peltola J, Nord J, Keinonen J and Averback R S 2001 *J. Appl. Phys.* **90** 1710
[8] Tomm J W, Strelchuk V, Gerhardt A, Zeimer U, Zorn M, Kissel H, Weyers M and Jimenez J 2004 *J. Appl. Phys.* **95** 1122
[9] Stelmakh N, Mangeney J, Alexandrou A and Portnoi E L 1998 *Appl. Phys. Lett.* **73** 3715
[10] Mageney J, Choumane H, Patriche G, Leroux G, Aubin G, Harmand J C and Oudar J L 2001 *Appl. Phys. Lett.* **79** 2722
[11] Tkachenko N V, Rantala L, Tauber A Y, Helaja J, Hynninen P H and Lemmetyinen H 1999 *J. Am. Chem. Soc.* **121** 9378
[12] Kalna K and Mosko M 1996 *Phys. Rev.* B **54** 17730
[13] Kersting R, Schwedler R, Wolter K, Leo K and Kurtz H 1992 *Phy. Rev.* B **46** 1639
[14] Deveaud B, Damen T C, Shah J and Tsang W T 1988 *Appl. Phys. Lett.* **52** 1886
[15] Oberli D, Shah J, Lewell J L, Damen T C and Chand N 1989 *Appl. Phys. Lett.* **54** 1028
[16] Deveaud B, Morris D, Barros A R X, Becker P and Gerard J M 1994 *Opt. Quantum Electron.* **26** S679 and references therein
[17] Marcinkevcius S, Olin S U and Treideris G 1993 *J. Appl. Phys.* **74** 3587
[18] Zhou X Q, Leo K and Kurz H 1992 *Phys. Rev.* B **45** 3886
[19] Ziegler J F, Biersack J P and Littmark U 1985 *The Stopping and Range of Ions in Matter* (New York: Pergamon)
[20] Ziegler J F 2003 SRIM-2003 software package, available online at http://www.srim.org.