Passive Q-switching of diode-pumped Yb:YAG microchip laser with ion-implanted GaAs

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We reported a passive Q-switched diode laser pumped Yb:YAG microchip laser with an ion-implanted semi-insulating GaAs wafer. The wafer was implanted with 400-keV As^+ in the concentration of 10^{16} ions/cm^2. To decrease the non-saturable loss, we annealed the ion-implanted GaAs at 500 °C for 5 minutes and coated both sides of the ion-implanted GaAs with antireflection (AR) and high reflection (HR) films, respectively. Using GaAs wafer as an absorber and an output coupler, we obtained 52-ns pulse duration of single pulse.

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Q-switching all solid-state lasers employing a solid-state saturable absorber are desirable for many applications such as micromachining, ranging, remote sensing, and microsurgery. Compared with the active Q-switching, passive Q-switching techniques can significantly simplify the operation, improve the efficiency, reliability and compactness, and reduce the cost of laser sources[1]. So far, a variety of solid-state saturable absorption materials have been investigated, such as LiF:F$_2$ and tetravalent chromium-doped crystals, applying to semiconductor saturable absorber mirrors (SESAMs) particularly those with the GaAs quantum-well structures[2-8]. SESAM is attractive as saturable absorber because its absorption coefficient, recovery time and saturation energy flunence can be designed and controlled. But SESAM is expansive and mainly used for passive modelocking. GaAs substrate is cheap for passive Q-switching. However, its absorption depth is limited and its recovery time is hard to be controlled. Ping Li *et al.*[2,3] obtained 80-ns pulse duration from passive Q-switched flash-lamp-pumped Nd:YAG laser and 140-ns pulse duration from passive Q-switched diode-laser-pumped Nd:YVO$_4$ laser using GaAs substrate as a saturable absorber and an output coupler. Here, we report 52-ns pulse generation from passive Q-switched diode laser pumped Yb: YAG microchip laser with an ion-implanted GaAs wafer as an absorber and an output coupler.

The photon energy at 1.06-μm wavelength is far below the GaAs band gap of 1.42 eV, the absorption at this wavelength is believed due to the EL2 defect that forms a deep donor level EL2^0/EL2$^+$ located 0.82 eV below the conduction band within the band gap as shown in Fig. 1.

EL2 is a defect energy level that normally exists in GaAs wafer. Under the laser illumination, transitions from EL2^0 to the conduction band absorb optical energy and produce free electrons in conduction band and positively charge donors EL2$^+$, while valence to EL2$^+$ transition produces free holes in valence band and neutral donors EL2^0. The absorption for this process is saturable with the increase in laser irradiance in GaAs. This absorption is taken as the single-photon absorption (SPA). There is a general understanding that GaAs can be used as passive Q-switch as a result of this saturable absorption. However, apart from SPA, there are also two-photon absorption (TPA) and free-carrier absorption (FCA) at higher laser irradiance. TPA generates free electrons in conduction band and free holes in valence band whereas FCA promotes electrons into the higher conduction band and holes into the deeper valence band. TPA also has effect on the formation of Q-switched pulse[2]. However, FCA only generates non-saturable loss. To avoid such loss, we choose semi-insulated GaAs substrate in our experiments. The concentration of semi-insulate GaAs is about 10^5 ions/cm^3, therefore its FCA is near zero. GaAs bulk materials grown by liquid encapsulated Czochralski (LEC) method have three to five times EL2 concentration as much as vertical gradient freezing (VGF) method, thus we often choose GaAs materials made by LEC method. Generally, the concentration of EL2 in semi-insulate GaAs made by LEC method is limited in the range between 1.0×10^{16} and 2.0×10^{16} ions/cm^3 because most of applications for GaAs wafer in microelectronics require least EL2 defect in GaAs wafers. We can change it by controlling the growing condition. In this study, we increase the concentration of EL2 by As^+ implantation. By this method, we can process the GaAs wafer freely by the implantation dose, energy and GaAs area to obtain the recovery time and saturation depth as designed.

We implanted 500-μm thick semi-insulating GaAs wafer with 400-keV As^+, with a dose of 10^{16} ions/cm^2. We simulate the profile of vacancy concentration generated after the implantation by program trim 95 as shown

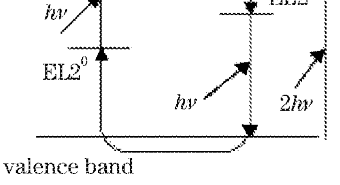

Fig. 1. EL2 defect energy level diagram.

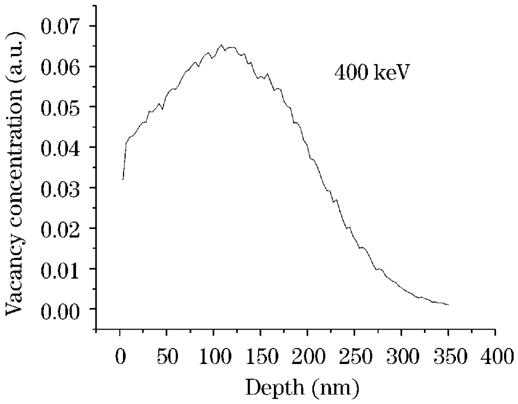

Fig. 2. The profile of vacancy concentration generated after 400-keV As^+ implantation into GaAs.

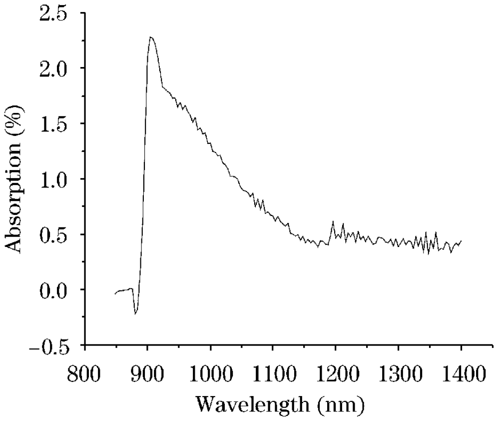

Fig. 3. The absorption difference between non-ion-implanted GaAs and ion-implanted GaAs.

in Fig. 2. The vacancy concentration is related to the concentration of EL2 generated after the ion implantation. The added EL2 defects after the ion implantation distribute near the surface of the GaAs wafer. The thickness of the implantation layer is about 400 nm.

To decrease the non-saturable loss, we annealed the ion-implanted GaAs at 500 °C for 5 minutes. When GaAs is annealed at lower annealing temperature, the Yb:YAG microchip laser cannot work because of too much loss, while at higher annealing temperature, the modulation effect is very weak. We also coated both sides of the ion-implanted GaAs with antireflection (AR) and high reflection (HR) films, respectively in order to make it work as an output coupler.

The absorption spectrum is shown in Fig. 3. The vertical axis represents the difference between non-ion-implanted GaAs and ion-implanted GaAs, which can be taken as the absorption that generated after the implantation. We think that it is related to the added EL2 concentration after the ion implantation. EL2 concentration increases very much after the ion implantation, which will be advantageous for Q-switching at 1.06 μm in solid-state lasers with GaAs absorber. We can see that the range of high absorption is from 900 to 1100 nm, which illustrates that we can use ion-implanted GaAs for the absorber in Q-switching of solid-state lasers at the wavelength near 946 nm.

Diode-pumped Yb:YAG lasers offer several advantages such as longer upper-state lifetime of 951 μs, which makes it very suitable for Q-switched pulse generation, lower thermal load per unit pump power and absence of excited-state absorption and up conversion losses, because of the simple energy-level diagram of Yb:YAG crystals. Figure 4 shows a schematic diagram of the experimental set-up. The cavity length is 1.2 cm, which is limited by the focusing lenses at the end of the fiber of 940-nm semiconductor laser. We also coated both sides of the ion-implanted GaAs with AR and HR film so that it has 2.8% output. Ion-implanted GaAs was used as an absorber and a coupler in the experimental set-up. A typical oscilloscope trace is presented in Fig. 5, showing a train of Q-switched pulses. The pulse to pulse

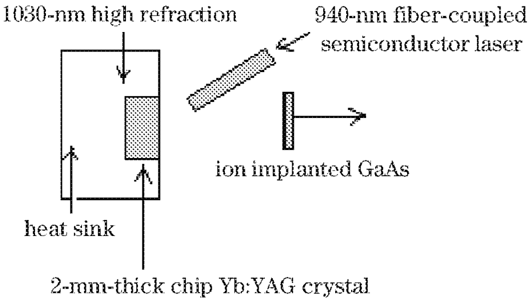

Fig. 4. Experimental set-up of passive Q-switched Yb:YAG microchip laser with ion-implanted GaAs.

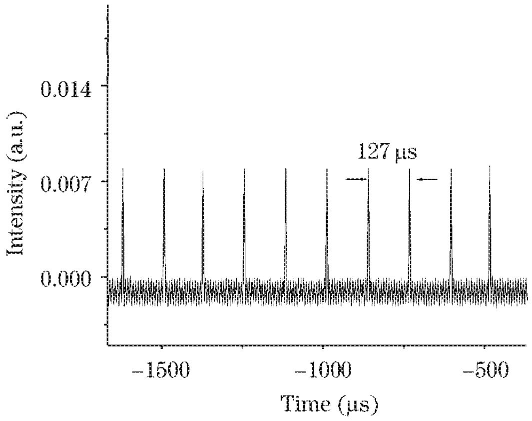

Fig. 5. Oscilloscope trace of passive Q-switching diode-pumped Yb:YAG microchip laser with ion-implanted GaAs.

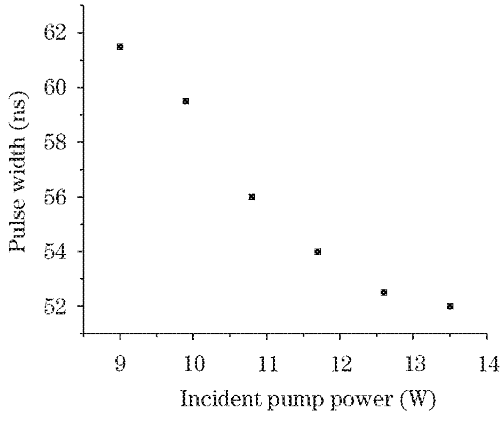

Fig. 6. Corresponding variation of the pulse width with the pump power.

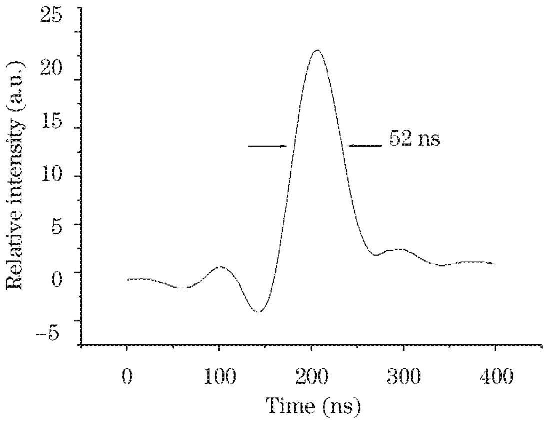

Fig. 7. Oscilloscope trace of a 52-ns pulse generated from Yb:YAG microchip laser.

amplitude fluctuation and interpulse timing jitter of the Q-switched pulse train were found to be less than ±10%. Figure 6 displays the corresponding variation of the pulse width as the pump power increases. An increase in the pump power resulted in a decrease of the pulse duration and the maximum pump power of 13.5 W. Figure 7 displaies the shortest single pulse, whose duration was 52 ns. The pulse energy remained relatively constant and reached a maximum level of 3 μJ at 10.8 W of pump power.

In conclusion, we implanted semi-insulating GaAs wafer with 400-keV As^+ ions, and the concentration is 10^{16} ions/cm^2. To decrease the non-saturable loss, we annealed the ion-implanted GaAs at 500 °C for 5 minutes. We also coated both sides of the ion-implanted GaAs with AR and HR films. Using ion-implanted GaAs as an absorber and an output coupler, we obtain 52-ns pulse duration of single pulse from passive Q-switched diode-pumped Yb:YAG microchip laser.

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