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Novel AlGaAs/CaF_2 SESAM Device for Ultrashort Pulse Generation

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ABSTRACT

A novel ultrabroadband AlGaAs/CaF_2 semiconductor saturable absorber mirror (SESAM) covering nearly the entire Ti:sapphire gain spectrum is demonstrated. This device supports sub-10-fs pulse operation of a laser. In contrast to previous SESAMs of comparable bandwidth, our device can be monolithically grown by molecular beam epitaxy and requires no post-growth processing. GaAs is used as semiconductor saturable absorber material. The high defect concentration of the material is due to the lattice-mismatched growth on a fluoride surface with (111) orientation. With a time response of 1.2 ps for carrier trapping, a saturation fluence of 36 $\mu J/cm^2$ and a modulation depth of up to 2.2% , the GaAs saturable absorber is well-suited for all-optical switching in SESAM devices used for ultrashort pulse generation.

INTRODUCTION

Devices based on semiconductor materials have been found many applications in ultrafast all-optical switching, in femto- and picosecond laser pulse generation, and in optoelectronics [1]. For example, semiconductor saturable absorber layers were introduced in optical devices to explore their nonlinear optical property of an intensity depending absorption for all-optical switching [2]. A semiconductor saturable absorber mirror (SESAM) basically consists of a high reflection mirror with a reflectivity of at least 95%, and a saturable absorber material. SESAMs rely on the operation of the absorber layer as an all-optical switch that is based on changes of reflectivity due to absorption bleaching induced by a strong laser pulse allowing for the self-starting of a laser.

Conventional SESAMs have been successfully fabricated by molecular beam epitaxy (MBE) using AlGaAs/AlAs multilayer stacks and GaAs saturable absorber. Laser pulses as short as 34 fs were generated with Ti:sapphire lasers using an AlGaAs/AlAs Bragg mirror with an imbedded single GaAs quantum-well layer [3]. However, these conventional SESAMs suffer from a narrow bandwidth caused by a small difference in the refractive indices of AlAs and GaAs. Shorter pulses were obtained by replacing the AlGaAs/AlAs Bragg mirror by a silver mirror in order to increase the high reflection bandwidth. This kind of a low-finesse AFPSA device, where the top reflector is formed by the interface semiconductor/air, supported sub-6-fs pulses [4]. These pulses are some of the shortest ever generated. However, the semiconductor saturable absorber cannot be directly grown on top of a silver mirror by epitaxy. Post-growth processing has to be applied, which complicates the fabrication process and may cause additional nonsaturable losses. Moreover, the silver bottom mirror only provides a reflectivity of less than 97%. Therefore, methods are continuously in development to avoid post-growth processing and to enable the monolithic growth of ultrabroadband SESAM devices.

With the demand for a larger wavelength tuning range of monolithically grown devices, semiconductor materials have to be combined with other materials like fluorides or oxides to increase the refractive index difference of the Bragg mirror pair [5]. In this paper, we demonstrate a monolithic ultrabroadband SESAM consisting of a two pair AlGaAs/CaF_2 Bragg mirror and a GaAs saturable absorber layer covering nearly the entire gain spectrum of a Ti:sapphire laser. The SESAM successfully started and supported mode-locking in a Ti:sapphire laser. This device was used for to generate laser pulses in the sub-10 fs range.

EXPERIMENTAL DETAILS

AlGaAs/CaF_2 SESAMs were grown by solid source molecular beam epitaxy (MBE) on GaAs (111)B oriented substrates. CaF_2 growth was carried out at a substrate temperature of 600°C and a growth rate of 0.2 μm/h. AlGaAs layers with 77% aluminum concentration were grown with 0.7 μm/h at 600°C. Growth was interrupted to anneal the surface under As_2 flux several times. The CaF_2 surface was exposed to a high energy electron beam of 20 keV at grazing incidence before the GaAs absorber overgrowth. A Varian Cary 5E spectrophotometer was used to measure the spectral reflectivity. The absorber layer was studied by saturation fluence and pump-probe measurements. All measurements were carried out at room temperature using an 80 MHz, 150 fs pulse train from a Ti:sapphire laser centered at 830 nm. A SESAM assisted Kerr-lens mode-locked Ti:sapphire laser described in Ref. [4] was operated by an AlGaAs/CaF_2 SESAM with GaAs saturable absorber layer.

DISCUSSION

The growth of AlGaAs and fluorides in multilayer stacks is governed by the lattice mismatch, by their thermal expansion properties and by the difference in their surface chemistry. The lattice mismatch is about 3.5% at room temperature but decreases to about 2.5% at growth temperature. In addition, the linear thermal expansion coefficient is three times higher for CaF_2 ($19.2 \times 10^{-6} K^{-1}$) than for GaAs ($6.4 \times 10^{-6} K^{-1}$). Therefore, large thermal strain is introduced to the layers during cooling down or temperature cycling. Severe crack formation to relax the thermal strain in (100)-oriented multilayer stacks is a consequence, which degrades the performance of a optical device. An alternative was a change in the growth orientation from (100) to (111) [6]. The (111) orientation is the preferred growth orientation of the fluorides. In addition, the mechanism of dislocation gliding allows for the relaxation of the strained layer [7]. The drawback in changing the growth direction is that GaAs has only a small growth window for the (111)-oriented growth. Furthermore, the layer quality is very sensitive to As/Ga ratio, which is much lower than that used for standard (100) GaAs growth. GaAs nucleates on CaF_2 by the formation of islands due to the low surface free energy of CaF_2 [8]. However, defects introduced to the absorber material by the growth mode offer a high density of defect states for carrier trapping. Therefore, GaAs grown on fluoride can be applied as saturable absorber material in optical devices for ultrashort pulse generation

For the fabrication of an ultrabroadband SESAM, the AlGaAs/CaF_2 Bragg mirror and the GaAs saturable absorber needed to be combined in one device. Therefore, a two pair Bragg mirror consisting of 140 nm CaF_2 and 70 nm $Al_{0.77}Ga_{0.23}As$ with a 170 nm CaF_2 spacer layer and a 40 nm GaAs saturable absorber layer on top was grown. This SESAM has a bandwidth of more than 300 nm for the nonsaturated reflectivity as shown in figure 1. The measured high reflection bandwidth is about five times larger than that of conventional AlGaAs/AlAs SESAMs. Furthermore, the number of mirror pairs is greatly decreased from more than 25 for

$AlGaAs/AlAs$ to only two $AlGaAs/CaF_2$ pairs. The $AlGaAs/CaF_2$ SESAM provides a linear reflectivity of 97% due to the large difference in the refractive indices of the materials forming the mirror. The GaAs saturable absorber layer showed a higher absorption for the nonsaturated reflectivity than calculated, which indicates that the high defect concentration in the GaAs increased the absorption coefficient of the material.

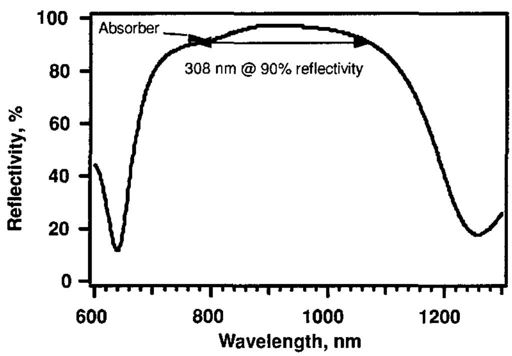

Figure1. Reflectivity spectrum of a $AlGaAs/CaF_2$ SESAM with GaAs saturable absorber layer.

The saturable absorber is described in terms of the modulation depth ΔR, the nonsaturable losses ΔR_{ns}, the saturation fluence F_{sat}, and the impulse response or recovery time τ_A [9]. The modulation depth is the maximum amount of saturable losses, which can be bleached. Nonsaturable losses ΔR_{ns} are residual losses, which cannot be bleached. They are caused by scattering on interfaces or surfaces, additional absorption from defect states or reflectivity losses from the bottom mirror. The saturation fluence describes the light intensity, which is necessary to bleach the saturable losses. The recovery time is a measure for the carrier relaxation processes. The approximately bitemporal recovery time has two components attributed to carrier thermalization and trapping/recombination. Epitaxially grown saturable absorber materials have typically slow recovery times on the order of nanoseconds due to the low defect concentrations in the layers. Therefore, defects have to be introduced to the material to provide additional defect states for faster carrier trapping. Methods to obtain fast saturable absorber materials are low-temperature (LT) growth by molecular beam epitaxy and ion implantation [10]. However, GaAs epitaxially grown on CaF_2 already provides high defect concentration at typical growth temperatures due to lattice-mismatched growth. Pump-probe experiments were carried out to study the impulse response. A biexponential recovery time of about 150 fs (thermalization) and 1.2 ps (carrier trapping/recombination) was measured as demonstrated in figure 2. This fast time response of the GaAs saturable absorber is excellent for the application as an all-optical switch in ultrashort pulse generation.

In general, a high defect concentration does not only contribute to the fast carrier trapping but can also cause additional absorption. Measurements of the saturation fluence and modulation depth reveal additional nonsaturable losses. A saturation fluence F_{sat} of 36 $\mu J/cm^2$ was measured for the $AlGaAs/CaF_2$ SESAM device, which can be compared with that of standard $AlGaAs/AlAs$ SESAMs. A modulation depth of 2.2% and nonsaturable losses of 2.7% are obtained. These losses can be mostly attributed to the designed bottom mirror since it consists of only two pairs.

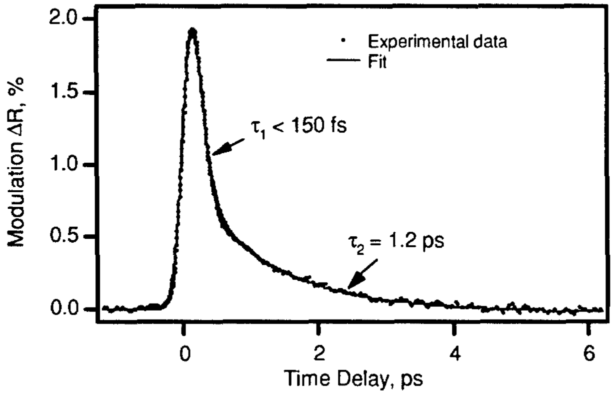

Figure 2. Nonlinear optical response and absorption modulation of the AlGaAs/CaF_2 SESAM measured in a pump-probe experiment (solid line – fit).

For short pulse generation, the SESAM was inserted in the cavity of a Ti:sapphire laser. The AlGaAs/CaF_2 SESAM successfully started and supported mode-locking in the laser. A pulse spectrum shown in figure 3 with a transform limit of 8.2 fs and pulses with a duration of 9.5 fs were measured. For the first time, the generation of ultrashort pulses below 10 fs with a AlGaAs/CaF_2 SESAM is proved. Due to the large high reflection bandwidth of more than 300 nm and the fast response time of the GaAs absorber, a broad pulse spectrum supporting sub-6-fs was measured with a different setup. That result shows the potential of AlGaAs/CaF_2 SESAM device for sub-6-fs pulse generation.

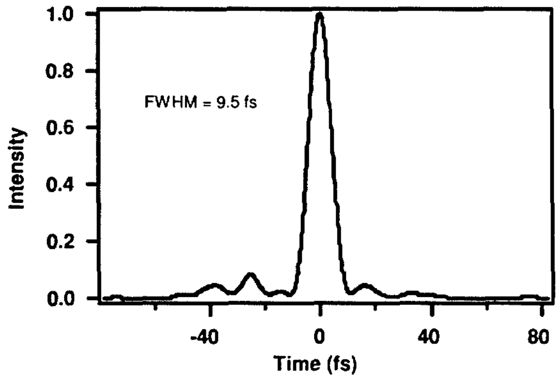

Figure 3. Sub-10-fs pulse generated by Ti:sapphire laser using an AlGaAs/CaF_2 SESAM.

CONCLUSIONS

We have shown that an ultrabroadband AlGaAs/CaF_2 SESAM device can be monolithically grown by molecular beam epitaxy. The large difference in the refractive indices of the AlGaAs and CaF_2 provide large high reflection bandwidth and makes this material combination very interesting for ultrashort pulse generation or broadband tunability. The generation of sub-10-fs pulses was possible with only six layers grown in one stack: two mirrors pairs, a spacer layer and a saturable absorber layer. The large reflection bandwidth of the AlGaAs/CaF_2 Bragg mirror, an the fast recovery times and low nonsaturable losses of the GaAs saturable absorber grown on CaF_2 allow for pulse spectra supporting sub-6-fs pulses.

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