In-situ Er-doped GaN optical storage devices using high-resolution focused ion beam milling

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Abstract. High-density GaN:Er optical storage devices were fabricated with focused ion beam (FIB) milling techniques. In-situ Er-doped GaN films (1–1.5 μm thick) were grown on Si substrates. To "write" a bit, the GaN:Er film was selectively milled with a 30-keV Ga^+ FIB. Data retrieval is accomplished by upconversion emission at 535/556 nm upon 1-μm IR laser stimulation. Regions where the Er-doped GaN layer is completely removed (and do not emit) are defined as logic "0," while regions that are not milled (and do emit) are defined as logic "1." Data patterns with submicron bit size (or 100 Mb/cm^2 density) have been fabricated by FIB milling. Data written by this approach has a theoretical storage capacity approaching 10 Gbits/cm^2. [DOI: 10.1117/1.1461833]

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GaN is a III-V wide bandgap semiconductor material that has been shown[1,2] to be an excellent host for light-emitting trivalent rare earths (RE^{3+}). The development of in-situ RE^{3+} incorporation during GaN molecular beam epitaxy growth has resulted in well-controlled doping of GaN samples. Upconversion light emission from RE^{3+}-doped GaN involves the absorption of two photons of the same or different energies producing the emission of a third photon of energy higher than that of either of the incident photons.[3,4,5] We have previously reported[6,7] visible green emission at 535 and 556 nm from GaN:Er excited by infrared (IR) laser sources at 840 nm or 1000 nm, or by both lasers simultaneously. The emission is related to radiative transitions to the $^4I_{15/2}$ ground state from the $^2H_{11/2}$ (535 nm) and $^4S_{3/2}$ (556 nm) excited Er^{3+} states. FIB milling with Ga^+ ions is a promising lithographic technique[8] due to its small beam diameter and high current density. Features smaller than 100 nm can be fabricated.

In this work, we report a data storage method based on upconversion from GaN:Er films patterned by FIB milling. This optical storage based on submicron FIB milling and RE^{3+} photon upconversion presents two distinct advantages: (1) a data mastering process based on existing, proven semiconductor fabrication technology; (2) the ability to capitalize on reliable and economical commercial IR laser sources. These advantages can lead to cost reduction and extended utilization of existing technology. Recording is achieved by FIB milling of submicron patterns on Er-doped GaN films. Data is retrieved by detecting the stepwise upconversion emission excited by the 1000 nm IR laser. Regions where the GaN:Er film was completely removed become opaque and serve as logic "0," while the unaltered regions, which emit upconversion luminescence upon IR laser stimulation, serve as logic "1."

The Er-doped GaN films were grown in a Riber 32 MBE system at a substrate temperature of 700°C, a Ga cell temperature of ~940°C, a N_2 flow rate of 1.5 sccm, and a plasma power of 400 W. The Er cell temperature was varied from 750 to 950°C to change the concentration. FIB milling is performed with the FEI FIB 200 system with a 30-keV Ga^+ ion beam. The FIB current was adjusted from 100 pA to 5 nA, depending on bit size. An indium-tin oxide cap layer was deposited on the GaN sample prior to FIB milling to reduce the damage. Arrays of bits of various sizes ($3 \times 3\ \mu m^2$ to $0.4 \times 0.4\ \mu m^2$) were fabricated.

To "read" the data, upconversion emission was obtained by pumping at 1000 nm with a 500-mW CW tunable diode SDL TC30 InGaAs/AlGaAs laser. The laser beam was focused to a ~10-μm diameter beam spot. The parallel readout of the memory was demonstrated by using a color CCD digital camera. Figure 1(a) contains microphotographs of FIB-milled arrays with 0.8- and 1.6-μm pitch. The 0.8-μm bits in the 1.6-μm-pitch pattern were fabricated with 5 nA

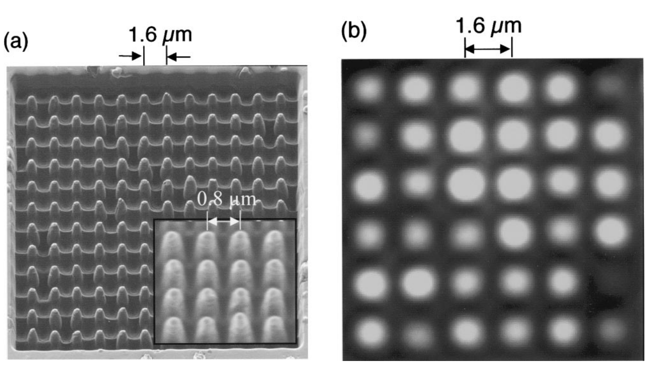

Fig. 1 1(a) Microphotographs of 1.6-μm-pitch and 0.8-μm-pitch bit patterns. (b) CCD optical image of upconversion emission from 1.6-mm-pitch bit pattern.

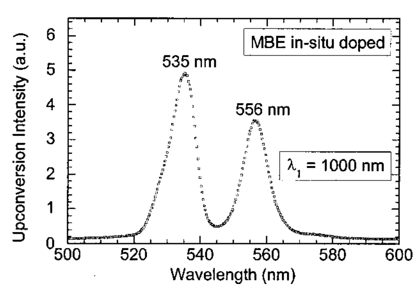

Fig. 2 High-resolution spectrum of green upconversion luminescence in an in-situ Er-doped GaN film excited by a laser at 1000 nm.

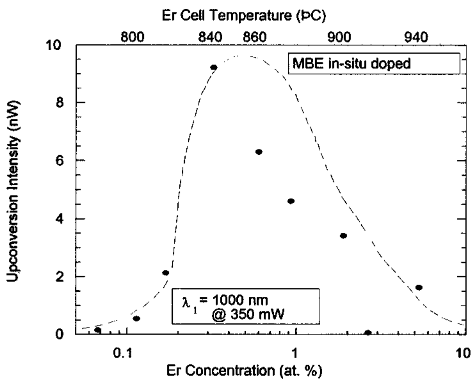

Fig. 3 Upconversion emission intensity of Er-doped GaN as a function of Er cell temperature and corresponding concentration.

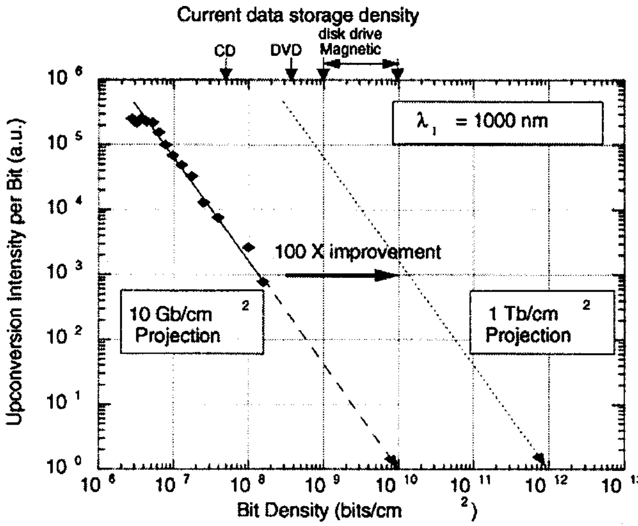

Fig. 4 Upconversion emission intensity versus current bit density (diamond data points). Maximum bit density of $\sim$10 Gbits/cm^2 is projected with current FIB milling parameters. To achieve terabyte storage capacity, a 100X improvement is required.

FIB current, while the 0.4-μm bit array used a 0.5 nA current. The upconversion image of the 1.6-μm-pitch array is shown in Fig. 1(b). The somewhat nonuniform upconversion intensity of the bits in the array is due primarily to the laser Gaussian beam profile and GaN:Er film variation.

As shown in Fig. 2, upconversion visible green emission at 535 nm and 556 nm was measured upon excitation at 1000 nm. Figure 3 shows the upconversion emission intensity as a function of Er concentration in the GaN film. The upconversion intensity increases rapidly with Er concentration up to 0.2–0.3 at.%. The GaN:Er film grown with Er cell temperature at 840°C had the highest upconversion emission intensity. Further increases in Er concentration lead to the quenching of the upconversion emission. This is very similar to the maximum in upconversion with concentration ($\sim$0.3%) observed[7] in Er-implanted GaN. Figure 4 shows the inverse relationship between emission intensity per bit and bit density. Intensity per bit is derived from the total upconversion intensity excited by a 2-μm-diameter laser beam divided by the total number of bits within the coverage of laser beam. The highest bit density attained so far is $\sim$150 Mb/cm^2 which is 3X greater than CD-ROM density but 2X smaller than DVD-ROM. This bit density was obtained with 0.4-μm bit size and 0.8-μm pitch. The extrapolation of 10 Gb/cm^2 bit density requires the FIB milling of bits with 0.1 μm pitch, as shown in Fig. 4. To reach terabyte storage capacity, a 100X improvement on current conditions will be needed. To obtain this improvement will require the use of a 980-nm pump laser for more efficient excitation, an increase in the optimum Er concentration, and the utilization of high-sensitivity detectors.

In summary, we have demonstrated the concept of Er-doped GaN optical memory devices using the upconversion process. An Er concentration of $\sim$0.25% was found to produce the highest upconversion emission intensity. Binary bit patterns were successfully recorded by means of localized FIB milling. A bit density of $\sim$150 Mb/cm^2 was achieved with a bit size of 0.4 μm and pitch of 0.8 μm. Extrapolation of this technique to 10 Gb/cm^2 will require the FIB milling of features with 0.1-μm pitch.

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