A promising candidate for a diluted magnetic semiconductor is the IV-VI ferromagnetic (FM) semiconductor Ge$_{1-x}$Mn$_x$Te. In contrast to the Mn-based III-V compounds, in Ge$_{1-x}$Mn$_x$Te the solid solutions exist over a very wide composition region and for a Mn concentration of x$_{\text{Mn}} \approx 0.5$ a maximum in the total magnetisation was theoretically predicted for cubic Ge$_{1-x}$Mn$_x$Te [1]. Furthermore, very recently a Curie temperature $T_C$ of around 190 K for films with a Mn concentration x$_{\text{Mn}} = 0.08$ grown by molecular beam epitaxy (MBE) has been reported [2]. Pure GeTe is well known as a ferroelectric semiconductor [3] due to its rhombohedrally distorted crystal structure. FM Ge$_{1-x}$Mn$_x$Te, however, shows a cubic NaCl structures for MBE grown samples for x$_{\text{Mn}} > 0.3$, hence it is a good candidate for a multiferroic semiconductor for x$_{\text{Mn}} < 0.3$. The crystalline structure and phase of MBE grown samples, however, depend strongly on the growth conditions, i.e. substrate temperature and excess Te$_2$ flux. We demonstrate that at a growth temperature of $T_S=335^\circ$C a crystallographic phase separation between cubic in [111] Ge$_{1-x}$Mn$_x$Te and hexagonal [001] MnTe is observed, proven by synchrotron x-ray diffraction (XRD) at the beamline BW2 at Hasylab as well as by TEM studies (see Fig. 1). Antiferromagnetic (AFM) MnTe exists either in a cubic ZB, or a hexagonal NiAs structure depicting different Neel temperature $T_N$ values of $\sim65$ K and $\sim310$ K, respectively.

We show exchange coupling within the decomposed samples consisting of three crystallographic phases: cubic FM Ge$_{0.48}$Mn$_{0.52}$Te, hexagonal AFM MnTe and rhombohedral Ge$_{0.82}$Mn$_{0.18}$Te. The coupling is revealed by an exchange bias as well as by a vertical shift of the FM hysteresis loop measured by SQUID magnetometry (not shown). The three phases are clearly determined by XRD (see Fig. 1a), whereas in TEM only the cubic Ge$_{0.48}$Mn$_{0.52}$Te phase and the hexagonal MnTe phase can be unambiguously distinguished (Fig. 1b). Reference samples grown at $T_S=310^\circ$C consisting of a single cubic [111] Ge$_{0.48}$Mn$_{0.52}$Te phase show no exchange bias. We found no evidence for
additional small FM precipitates with an incoherent crystal structure, like e.g. Mn$_3$Ge$_3$ precipitates within Ge$_{1-x}$Mn$_x$ [4]. To further study the exchange coupling between FM GeMnTe and AFM MnTe we have realised several well defined multilayer systems: First, a bi-layer consisting of 80 nm cubic ZB MnTe and of 100 nm cubic Ge$_{0.55}$Mn$_{0.45}$Te layers. The MBE growth of ZB MnTe is achieved by choosing a $T_S$ value of 450°C, whereas the subsequent Ge$_{0.55}$Mn$_{0.45}$Te layer is grown by only 315°C, respectively. The good layer quality is proven by synchrotron XRD (see blue line in Fig. 2a), measured at the beamline BW2 at Hasylab. From the thickness fringes around the cubic MnTe (111) Bragg peak we derive a MnTe layer thickness of 84 nm. The second multilayer system is fabricated at $T_S = 315°C$, where first a 20 nm pure GeTe layer (a = 5.98 Å) was grown to relax the misfit strain with respect to the BaF$_2$ (a = 6.2 Å) substrate, followed by 80 nm hexagonal MnTe and finally 90 nm cubic Ge$_{0.55}$Mn$_{0.45}$Te. The thickness fringes related to all three layer thicknesses indicate a very good epilayer as well interface quality of the whole system (green line in Fig. 2a).

Fig. 2 (a) Radial XRD scans along $q_z$, i.e. along the (111) growth direction, of multilayers consisting either of 80 nm cubic ZB MnTe (blue) or hexagonal MnTe (green) and 90 nm cubic Ge$_{0.55}$Mn$_{0.45}$Te, respectively. Thickness fringes related to the different layer thicknesses are clearly revealed. (b). 2D reciprocal space map of 100nm EuTe and 200 nm Ge$_{0.93}$Mn$_{0.07}$ measured at a lab source. All samples are grown on (111) BaF$_2$ substrates.

Furthermore, very recently we was able to combine 100 nm AFM EuTe ($T_N = 9.6$ K) with 200 nm rhombohedrally distorted Ge$_{0.93}$Mn$_{0.07}$Te to a well defined bi-layer system as shown in the XRD 2D reciprocal space map in Fig. 2(b).

This allows us to combine three AFM semiconductors depicting different $T_N$’s with FM Ge$_{1-x}$Mn$_x$Te with adjustable $x_{Mn}$. Exchange bias in the MnTe/Ge$_{1-x}$Mn$_x$Te multilayer systems is observed in SQUID measurements, which shows that this material system is promising for multiferroic semiconductor heterostructures, in which the magnetic properties can be adjusted by tuning the crystallographic properties of the single layer materials.

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References