

distance between the nanoparticle tag and the top surface of the free magnetic layer very small, from about 6 nm to about 30 nm. Furthermore, this could circumvent current crowding (van de Veerdonk, R. J. M., et al., *Appl. Phys. Lett.*, 71: 2839 (1997)) within the top electrode which would likely occur if only a very thin gold electrode were used.

[0067] Except that the sense current flows perpendicular to the film plane, the MTJ detector can operate similarly to the spin valve detector, either with in-plane mode or vertical mode. The disclosure on EMI rejection and ultrathin passivation also applies to MTJ detectors, but to the advantage of MTJ detectors, the first top electrode of thin gold on MTJ also serves the triple purposes of electrical conduction, ultrathin passivation as well as specific DNA probe attachment.

[0068] At the same detector width and particle-detector distance, MTJ detectors give appreciably larger signals than spin valve detectors. For example, for an MTJ detector with a junction area of $0.2 \mu\text{m}$ by $0.2 \mu\text{m}$ and resistance-area product of $1 \text{ k}\Omega\text{-}\mu\text{m}^2$, operating with a MR of 25% at a bias voltage of 250 mV, and $H_b=35 \text{ Oe}$, $H_t=100 \text{ Oe rms}$, the voltage signal from a single 11 nm diameter Co nanoparticle whose center is 35 nm away from the free layer midplane is about $20 \mu\text{V}$, roughly an order of magnitude larger than those listed in Table 1 for similar-sized spin valve detectors. This is a great advantage for MTJ detectors over spin valve detectors. In accordance with the present invention, MTJ detectors suitable for use in practicing the invention can have junction areas from about $0.01 \mu\text{m}^2$ to about $10 \mu\text{m}^2$, and resistance area products from about $0.1 \text{ k}\Omega\text{-}\mu\text{m}^2$ to about $100 \text{ k}\Omega\text{-}\mu\text{m}^2$.

[0069] DNA Quantification and Dynamic Range

[0070] Single-tag detection has been previously demonstrated both experimentally (Li, G., et al., *Journal of Applied Physics*, Vol. 93, no 10 (2003), p. 755.7) and theoretically (Li, G., et al., *IEEE Trans. MAG*, Vol. 39, no. 5 (2003), p. 3313) in prototype MagArray™ detectors. In real applications, however, multiple particles may be on a detector, and their locations are likely not at the center of the detector surface. We found that the voltage signal from a single particle strongly depends on its lateral location on the detector surface, more so in the hard-axis direction (y-axis in FIG. 2A) of the free layer than in the easy-axis α -axis in FIG. 2A). The calculated time-domain voltage signal under a sinusoidal tickling field versus the y-axis of an 11 nm diameter Co nanoparticle whose center is 25 nm away (z-axis in FIG. 2A) from the top surface of the free layer can be measured. The 2f signal gets distorted near the sensor edge and drops rapidly at the edge. Note that the overall detector signal is larger at the detector edge, but it consists of mostly 1f components which are out of phase at the two edges.

[0071] In order to count the magnetic nanoparticles quantitatively based on the amplitude of the voltage signal, we want each particle to generate the same signal regardless of its location. A spin valve detector may not allow us to quantify the number of particles accurately. The MagArray™ detector adopts a detection window which removes the nonuniformity near the edge. Note that the two-layer top electrode designs for MTJ can remove the edge uniformity as long as we make the Au window sufficiently smaller than the active junction. Depending on the detector geometry and

the tolerance to signal variations, coverage of about 50% of active detector area may be desired.

[0072] The detection window described above allows the MagArray™ detector to count multiple nanoparticles (NP) very well. Based on the assumptions of equivalent averaged magnetic field of NPs and coherent magnetization rotation of the free layer, we have calculated the detector signals of multiple magnetic NPs uniformly or randomly distributed over a rectangular area somewhat smaller than the active detector area. For example, for a $4 \times 0.3 \mu\text{m}^2$ spin valve (SV) detector, the normalized signals of uniform NP arrays versus the actual NP numbers for different array aspect ratios can be determined. At low particle numbers the signal is fairly linear, and only at high particle numbers does the signal linearity degrade. A higher aspect ratio gives better signal linearity because more NPs are away from the sensor edges. The mean values and standard deviations of the normalized signals for randomly distributed NPs can be determined, which also indicates good signal linearity. We have done experiments on a monolayer of 16-nm Fe_3O_4 NPs coated on $0.3\text{-}\mu\text{m}$ wide SV sensors to verify the model.

[0073] These results indicate that the detector can not only detect 1-10 NPs but also count hundreds of NPs with a resolution of a few NPs, far exceeding the detection limit of state of the art optical microarrays. Furthermore, we could multiplex a set of detectors with various sensor widths and lengths such that the smaller detectors can sense low concentration biomolecules while the larger ones can sense and count high concentration biomolecules.

[0074] Nucleic Acid Probes Attached to Detector

[0075] An additional embodiment of the invention is directed towards nucleic acid probes (e.g. DNA or RNA) attached to a detector.

[0076] An oligonucleotide probe (binding molecule) complementary to the DNA fragment of interest (target molecule) is attached to the surface directly above the detector via a 5' linkage. To this end, the surface of the detector may be coated with a thin layer of glass or gold, and probe DNA may be attached. The attachment of probe DNA to glass surfaces via poly-L-lysine or to gold surfaces via a thiol linkage is widely practiced in biochemistry. Alternatively, a monolayer of self-assembled probe DNA can be prepared directly on the surface of the detector with no additional fabricated layer between the detector and the probe DNA.

[0077] The 5' end of the target DNA is labeled with a magnetic nanotag. During the hybridization step, the magnetically labeled target DNA attaches specifically to the immobilized probe DNA on the surface of the detector. It is highly preferred that the distance between magnetic tag and the free layer in the detector be kept to a minimum, since strength of the magnetic signal will be compromised if the distance between the detector and the signal is too great. One scheme is to apply an external magnetic field gradient during the hybridization step to concentrate target DNA and to pull the magnetic tag closer to the detector surface after the hybridization step. The external magnetic field may also be used to remove non-hybridized tagged DNA fragments.

[0078] Array Architecture

[0079] We have designed an architecture for the MagArray™ detector that is suitable for quantitative detection of