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Deformation and fracture of silicon electrodes in lithium-ion batteries

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ABSTRACT

We have performed a number of experiments to examine the mechanical behavior of amorphous silicon electrodes of lithium-ion batteries. In particular, we have measured the fracture energy of lithiated silicon thin-film electrodes as a function of lithium concentration. The fracture energy is found to be similar to that of pure silicon and essentially independent of the concentration of lithium. Thus, although lithiated silicon can flow plastically, it appears to fracture in a brittle manner. We have also varied the rate of lithiation of amorphous silicon thin films while simultaneously measuring stresses. Increasing the rate of lithiation resulted in a corresponding increase in the flow stress. These observations indicate that rate-sensitive plasticity occurs in a-Li \times Si electrodes at room temperature and at charging rates typically used in lithium-ion batteries. Using a simple mechanical model, we have extracted material parameters from our experiments, finding a good fit to a power law relationship between the plastic strain rate and the stress. The observations of rate-sensitivity provide insight into the unusual ability of a-Li \times Si to flow plastically while fracturing in a brittle manner. Moreover, the results have direct ramifications concerning the rate capabilities of silicon electrodes: faster charging rates (i.e., strain rates) result in larger stresses and hence larger driving forces for fracture.